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The efficient collection and long term storage of solar
energy in the U.K., using air as the working fluid.

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Abstract

This thesis describes the results of four years work on the design, construction, testing and evaluation of a high performance air heating collector designed to supply heat to a communal interseasonal store, which could heat many houses all the year round in the U.K.

Interseasonal storage utilizing a pebble bed was investigated but shown to be costly both in terms of money and energy. The performance of medium to high temperature storage is shown to improve with high performance collectors.

The level of insulation specified in the 1978 Building Regulations is found to be inadequate for solar heating with long and short term storage, because it is more economic to add more insulation than to install solar heating.

While investigating the interseasonal storage of solar energy in pebble beds, data on the design and operation of air heating solar collectors was found lacking. Therefore the development and testing of both a high and low performance solar air heater was undertaken.

The standard methods of testing collectors and in particular high performance collectors are shown not to provide an adequate method of comparing the daily efficiency of various types of collectors. Methods of testing air collectors are

(ii)

presented under transient conditions more representative of collector operation in the U.K. The parameters affecting high performance collectors are examined, in particular the reduction of heat loss between cover and absorber, and the effect on performance of diffuse and transient radiation. Results are also presented for testing a low cost plastic collector.

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Preface

It would be false to suggest that the work included in this thesis was carried out by spending 6 months in the library researching the background and defining a problem, 18 months developing a method and testing a hypothesis with a computer model or experimental apparatus, 6 months taking results and then 6 months writing it up and arriving at a conclusion to the original problem, the thesis then being written up in the logical fashion of Introduction/Review, Method Results and Conclusion.

Research is very rarely like this and particularly so in the Applied Sciences where the solution of one problem leads to the discovery of another problem in another field and where many external factors are brought to bear.

The work reported here commenced in 1979 on a SERC studentship awarded to the Energy Research Group and has involved four years research.

The Energy Research Group was set up following the 73 'energy crisis'. Since then it has attempted to build a coherent picture in which energy sources, conversion and use fit together harmoniously to form an integrated whole. This is in contrast to the more generally held view that the 'energy problem' is primarily a supply problem.

By 1979 the Group had identified several novel energy technologies which were particularly suited to meeting various energy demands. This thesis is based upon one of these, that of interseasonal storage and in particular one novel design of collector and store 'Prometheus' proposed by Dr. B.W. Jones.

This work was a radical shift for the Group from policy paper studies to technological research and development and was made all the more difficult since the University itself was at that time relatively new to the field of research, which meant that laboratories were lacking in all those little things lying tucked away in corners, and which are essential for technological development.

The initial, rather ambitious project of developing a working prototype of an interseasonal heat store fed by solar collectors, soon proved very difficult due to the lack of technical expertise, equipment and funds. Several of the original design assumptions were found to be incorrect and for those which were initially assumed to be well understood knowledge was found lacking, in particular the heat transfer from collector to fluid, the design and operation of high performance collectors, and the heat transfer within a pebble bed with no fluid flow. The work retreated from the harsh outdoors to the more predictable indoors, and the system was reduced to its various components, store and collector, the work load being shared between two research students.

M. Golshekan carried on the work of heat transfer within a pebble bed store and I continued with the development of high performance air collectors. Standard methods of testing were found to be expensive in time and money, and not representative of collector operation. Alternative test methods were therefore examined. While examining the potential of honeycomb structured collectors for use as high performance collectors, a low performance collector was developed, which appeared to overcome several of the problems experienced in air collectors. Although low performance collectors are only suited to low temperature operation this design has the advantage of being cheap, light and easy to install. Such a device was seen to be more likely to be adopted. As interest in renewable energy in general, and solar energy in particular plummeted, due to the economic recession, the demand dropped and capital investment was at a low, North Sea Oil came on stream and again fossil fuels were relatively cheap. A change of American President meant a change of U.S. policy and the axing of solar research in the States. In the U.K. solar energy research was condemned without proper trial. Passive solar was the only survivor as it incurred no extra capital costs. Funding for active solar energy research was limited to systems which could show a rapid payback. Under such pressures attracting funding for long term research into interseasonal storage which required large capital expenditure became a dream.

(ix)

Our gorging of fossil fuels will eventually come to an end and work on renewables will again flourish.

(x)

Acknowledgements

Many people have assisted me during the course of this work, and I wish to express my gratitude to them all:

to my supervisor Dr. Barrie Jones who has helped with advice, constructive criticism, enthusiasm and as a friend;

to my parents without whose loving, help, kindness and faith this work would have never been started or finished;

to the Science and Engineering Research Council for providing the funds to start my work;

to The Open University for providing laboratory space and capital equipment, to the Energy Research Group for lively debate and a pleasant atmosphere in which to work;

to my friends who suffered the ordeal of my thesis and the secretaries who had to read and type it.

Without these people's help this thesis would not exist.

CHAPTER 1 Introduction

The other chapters in this thesis examine the application of solar energy in the U.K., from a U.K. perspective. This chapter outlines the importance of solar energy from a world perspective, and examines why the development of solar energy in the U.K. is more appropriate than in many other sunnier but poorer countries.

In 1979 the world used the equivalent of 6,960 million tonnes of oil equivalent (3.1×10^{20} J) [1]. The estimated recoverable fossil fuel reserves are $\approx 23 \times 10^{22}$ J [2]. At present rates of consumption, fossil fuels will not be depleted for ≈ 740 years. However world energy consumption is likely to rise for several reasons.

- (i) At present the majority of energy is used by the minority of the world's population, namely by that constituting the developed nations.

The quality of life in a country can be represented by a 'physical quality of life index' (PQLI), this combines life expectancy, infant mortality and literacy, into one index [3]. A plot of PQLI against energy consumption per capita for several countries is shown in Figure 1.1(a). Note that I have used PQLI instead of the more commonly used value of Gross National Product (GNP) which is less representative of the quality of life since it takes no account of

disparity in income, that is, it assumes the improvement in quality of life is the same if one person spends £10000 as if ten people spend £1000, and if a rich person spends £10 and a poor person spends £10. GNP has been defined as a measure of 'how rapidly a nation can release energy, pollute the environment and fill its dustbins' [4]. Figure 1.1(a) shows that an increase in PQLI involves an increase in the energy consumption per capita - up to a point. It is fair to assume that all countries with a low PQLI would like a quality of life similar to that of Sweden. This in turn would mean an increase in energy consumption by the under developed countries. This is of course not to say that these countries should not learn from our mistakes: compare the energy consumption of Sweden with the U.S.A. Sweden uses almost half as much energy per capita as the U.S.A. yet has a higher PQLI. The developed nations appear to have now reached a saturation in their energy consumption. This is demonstrated by the fact that from 1974 to 1979 the energy consumption has increased at an average of 7% per annum in South East Asia compared to 1.8% for Western Europe [5]. The bar chart Figure 1.1(b) shows the average per capita energy consumption for all the people living in countries with a PQLI of 10 to 20, 20 to 30 ...etc. The percentages shown in each bar are the percentage of the world population

within that range of PQLI. At present 73% of the world's population has a PQLI of less than 90. If increasing the PQLI to above 90 means an average energy consumption of 5600 kg of coal equivalent (as suggested by Figure 1.1(b)), and if everybody in the world were to have a PQLI greater than 90 (i.e. 5600 kg of coal equivalent per capita), then the world energy consumption would increase by a factor of three. Thus if all the countries were to obtain a PQLI of greater than 90, I would expect the recoverable reserves of fossil fuels to only last ~ 250 years.

- (ii) The world population is doubling every 33 years [9], with the most rapid population increase in the countries with the smallest PQLI.
- (iii) Even if the PQLI and population remain constant and so product consumption remains constant, as mineral resources become depleted, which will occur more rapidly than the depletion of fossil fuels [3], more energy will be required to extract the same quantity of mineral resources.

Clearly energy demand is likely to increase. Fossil fuels are however going to find it more difficult to meet such demands because of the limits of the resource and the environmental pollution associated with burning fossil fuels

[6]. Renewable energy offers the potential to solve this problem.

A renewable energy resource is one which is replenished at the same rate as it is used and therefore should really be called a balanced energy source, because even oil is renewed after many millenia. Energy used directly from the sun is renewable.

Solar energy appears to be a very appropriate energy resource for under developed countries because:-

- (i) under developed countries are generally the more sunny areas of the world,
- (ii) a large infra structure for the distribution of fossil fuels is not yet in existence in the very dispersed communities of the under developed nations, making the use of fossil fuels less economic,
- (iii) under developed countries are more likely to increase their energy demand than the developed countries because the quality of life and population is likely to increase more than in the developed countries.

So why is it the developed countries which have the largest utilization of solar energy? The answer lies in the capital cost of utilizing solar energy. Because solar energy is very dilute ($< 1200 \text{ W m}^{-2}$) when compared to fossil fuels, the capital cost of utilizing solar energy compared to fossil

fuels is large. This is highlighted by the fact that one cubic metre of oil contains ≈ 1000 times the energy that can be collected from a 1 m^2 collector placed in the sunniest part of the world over a period of a year, and whereas all the energy from the oil can be harnessed at will, the solar energy is only available when the sun is shining and not necessarily when the energy is required. It is this dilute intermittent nature of solar energy which makes it capital intensive, as large collecting surfaces and storage volumes are needed. So solar energy by its very nature involves large capital expenditure. However, solar energy does have low running costs when compared to fossil fuels which generally have a high running cost because of the price of fuel, but a small capital cost. The benefits of solar energy can therefore only be recouped after a long period of time. It is for this reason that under developed countries cannot afford to use solar energy as they have limited capital. So telling under developed countries not to use fossil fuels but to use solar energy is like telling a starving child not to buy expensive food but to buy seeds instead and grow them for food. Although the benefits of the seeds will be greater in a years time, the child will be dead by then. Therefore, it is only the wealthier nations which can afford to invest in solar energy, it also happens of course that these nations are the ones which have exploited fossil fuel reserves the most.

One could of course argue that we should forget about the

under developed countries and carry on doing what's good for us. The 'Brandt Report' [5] has however identified that the continued state of the developed world is dependent on removing the plight of the under developed world. For example, the U.K. is now linked to the EEC, which in 1979 imported some five times more oil than it exported, mostly from the politically unstable Middle East [5].

It is for these reasons that this thesis examines the application of solar energy in the U.K., to reduce fossil fuel demand, not because the U.K. is technologically the best place for such development, although it is not vastly inferior, but because it can afford to do so. This is, of course, not to say that under developed countries should not try to use solar energy. Many of the conclusions reached in this chapter are however relevant to countries other than the U.K., principally those with a similar latitude and a maritime climate. In particular Western Europe, for which it has been estimated that by the year 2020 up to 50 million tonnes of oil equivalent could be provided annually by solar energy [7].

If solar energy is to be implemented it must be based on a sound technological and economic basis. Chapter 2 of this thesis examines the potential for solar energy to meet the U.K. annual demand for domestic space heating and hot water all year round, which in 1976 consumed some 18% of the fossil fuels used in the U.K. [8]. Active solar heating is the most

appropriate renewable source for this demand of low grade heat ($< 80^{\circ} \text{C}$). In particular the design of an air heating system (Prometheus) is investigated, in particular its ability to be a net producer of energy, and its ability to compete with fossil fuels. Chapter 3 examines the potential for limiting our consumption of energy for domestic heating and the implications of this for active solar heating.

An air heating solar system was considered to offer several advantages over the more conventional water heating solar system. Little work has been carried out in the U.K. on the use of air systems - see Chapter 4. Before solar heating systems can be widely adopted there must be methods of testing them. Chapter 5 examines methods of testing air collectors and in particular the differences in testing in the U.K. and in the U.S.A. Several of the results are also relevant to water collectors.

The development of a high performance collector was established to be a key component in an interseasonal solar heating system. Therefore methods of improving the performance of collectors operating in the U.K. are examined in Chapter 6. The reduction in heat loss from the cover to the absorber was identified as a key component in increasing collector performance. Hence methods of measuring and reducing this heat loss are examined in Chapter 7.

The operation of a cheap, moderately efficient collector made

of plastic was also investigated. This type of collector has a low thermal capacity and can replace conventional roofing materials for little extra cost.

During the four years research that is contained in this thesis a change in aim from assessing total interseasonal storage systems to a more detailed study of air collector design occurred because there was not enough information on air collector design to construct a Prometheus type system and the funds and manpower required to make a detailed study of a large scale solar system were not available.

Note that wherever possible prices quoted in the text of this thesis are those at the year of costing. They have not been converted to a current cost by the use of a Retail Price Index (RPI). This is because the RPI is for a conglomeration of materials and hence a converted price may not be accurate. Secondly, the date of the pricing reflects how old the technology was when it was assessed.

CHAPTER 2 Solar systems using long term storage

2.1 Why do we need long term storage of solar heat in the U.K.?

2.1.1 The problem

35% of U.K. delivered energy goes to producing low grade heat ($< 80^{\circ}\text{C}$) [1] which consumes 32% of U.K. primary energy [2]. Solar energy is particularly well suited to supplying low grade heat. The breakdown by fuel for supplying low grade heat is shown on the right hand side of Figure 2.1. Note that solids, liquids and gas meet similar shares of the load. These resources are likely to experience difficulties in meeting the future demand. The left hand side of Figure 2.1 shows a breakdown of the present energy use and also the predicted future energy use, as predicted by two differing scenarios reported in 'Energy Paper 39' (EP39) [2] and the International Institute for Environment and Development (IIED) [1]. Whether future demands could be met with conventional fuels is difficult to predict as shown by the poor track record of past predictions [3]. This is particularly difficult because as resources become more limited then prices rise, which in turn makes larger resources economic for extraction. Also the rate of demand and supply is dependent on so many factors other than purely economic ones, such as politics, economic growth, and the availability of existing infrastructure.

(a) Gas. The estimated reserves of North Sea gas are 35 to 80 trillion cubic feet. At the present rate of consumption the U.K. could use up the remaining reserves in 14 to 40 years. So a sharp decline in North Sea gas production is expected by the turn of the century. But the existence of a substantial national gas transmission and distribution system should make it possible to use imported liquified natural gas, or substitute natural gas (SNG) derived from oil or coal or pipeline imports from the Middle East and Russia. However, this will cause a trebling in the real price of gas by the turn of the century and could lead to a dangerous dependence on imported fuels.

(b) Coal. U.K. coal reserves should last 300 years at the present rate of consumption. But the U.K. demand for coal seems likely to expand considerably, as SNG replaces North Sea gas, and possibly as coal based liquid fuels replace North Sea oil, and coal is used instead of oil and gas for industrial heating and steam raising. There is no resource constraint on coal over the next forty years. However the ability of coal mines to expand at the fast rate to replace gas and oil is limited by the high capital needed, and the lack of experienced manpower to both develop and manage the pits. These factors, plus the need to work increasingly deeper and more difficult seams, will cause an estimated doubling in real coal prices by 2025.

(c) Oil. According to the Department of Energy the amount of oil that will be recovered ultimately from the U.K. continental shelf (not just the North Sea) will be in the range of 18 to 33 billion ($\times 10^{12}$) barrels. So far 1 billion barrels have already been extracted, and the U.K. is presently just "self sufficient" in oil (in terms of quantity, as we need to import heavier oils from the Middle East) extracting 1.8 million barrels a day. With the present rate of consumption, our reserves will last 27 to 46 years. But world oil prices will rise markedly because the production of national petroleum can no longer keep pace with the growth in world oil demand, causing a doubling in world prices in real terms by 2000, with a further 50% increase by around 2020. Even though the U.K. has its own oil supply, its prices are linked to world market prices because we need to sell lighter North Sea oil for heavier Middle East oil. In the first quarter of 1980 when we were just "self sufficient" the U.K. exported about 45% of its total North Sea oil production. More recent forecasts show only OPEC countries producing oil in more than 20 years time [3].

(d) Nuclear Fuels. With predicted increases in world uranium demand due to a world nuclear programme of approximately 1000 GW by the year 2000, increasing to over 3000 GW by 2025, the estimated uranium resources of the world would be used up by 2010. These estimates of world generating capacity now appear high, as cutbacks in nuclear programmes world wide have taken place because of high costs

and safety fears (in 79, NUKEM predicted 754 GW of world nuclear capacity in 2000 [4]). The U.K. (like most West European countries) has to import its uranium, which has become a political weapon for exporting countries, and recent attempts to evaluate indigenous resources have led to very stiff local opposition in the Orkneys. So the U.K.'s uranium availability is not assured. This has led the U.K. government to look at fast reactors. However, these will have high capital costs and anyway are still at the development stage. Also the supply of heat from nuclear fuels has to be questioned, because under certain circumstances the construction of nuclear reactors and the processing of the nuclear fuel can use up more fossil fuel energy than the electrical energy generated by them [5].

In the long term all these forms of energy which are not renewable disturb the climate by changing the atmospheric heat balance [68].

So where does the government see low grade heat coming from in the future? Although there may be a short term slump in demand due to the economic recession, if this is not to continue demand will invariably pick up. When it does, large price increases are expected in oil and gas due to finite resources, with coal finding it difficult to meet the market load, and environmental pressures against nuclear energy. According to EP39, by the second or third decade of the next century, the major source of energy for domestic heating will

be SNG, with some electric power, whilst industry will obtain its low grade heat from coal fired boilers. Renewable technologies provide less than 1% of the low grade heat* (equivalent to 1 million tonnes of coal equivalent per annum), as follows

- (i) Solar water heating
- (ii) Passive solar space heating
- (iii) Solid fuels from crops, and organic wastes
- (iv) Geothermal heat.

If more of the low grade heat demand can be met by active solar energy, this would release valuable resources of high density energy for other uses, where replacements do not exist, for example, transport. To do this, we must look at the present and future demand for low grade heat and tie this up with the supply of solar energy available in the U.K.

2.1.2 Demand

Table 2.1 shows the breakdown of U.K. demand for low grade heat. 95% is used for space and water heating in the industrial, commercial and domestic sector.

* In energy paper 39, low grade heat corresponds to less than 120° C, which makes up 39% of U.K. delivered energy compared with 35% delivered energy for low grade heat as defined in this thesis (< 80° C).

The domestic sector consumes 55% of the total energy used for space and hot water heating and so is the largest consumer of this type of energy. In order to examine methods of meeting this demand for energy it is important to understand how the demand varies, and how it is likely to vary in the future.

The space heating demand per house varies spatially in the U.K. depending on the latitude and height above sea level. This affects not only the total energy required but also the period over which energy is required during the year, i.e. the length of the heating season.

Temporal variations in space heating occur daily, normally reaching a maximum at nine o'clock at night when occupants require high internal temperatures coinciding with low external temperatures, and annually with a maximum in the winter as shown in Figure 2.2.

The weather varies from year to year causing variations in the annual heating consumption. On the basis of the last 25 years' weather data the coefficient of variation of annual heating degree-hours is close to 4% [6].

The energy consumption for space heating in each house varies depending on the level of insulation. However, even in identical housing the energy consumption varies due to the occupant, because of varying levels of human comfort and social habits. This can cause identical houses to consume up

to six times more energy, see Figure 2.3.

The hot water demand shows little seasonal variation.

However, large variations can occur from week to week and from house to house - Figure 2.4 and 2.5.

The combination of all these factors can produce a large variation in the quantity of energy required by each house and also when this energy is required.

Predicting what the future demand is likely to be is also very difficult as social habits are likely to change with the coming of the micro electronic age and increasing unemployment, increasing the daytime house occupancy. Changes in the levels of indoor clothing and insulation standards will also affect heating demand.

The domestic sector is the largest consumer of low grade heat and also the most well understood because it is the most uniform whereas the other two sectors vary according to their product. It is for these reasons that this thesis concentrates on the domestic sector. This is not to say that low temperature solar energy cannot play a significant role in the other sectors.

40% of the energy demand in the industrial sector is for low grade heat for process, space and hot water heating [9]. The matching of solar supply with demand for process heat in the

industrial sector is less of a problem than with domestic heating as a lot of process heat demand is continuous throughout the year, also the demand for industrial space heating occurs during the day, in phase with the solar supply. 60% of the industrial demand for space and water heating is at present supplied by expensive-to-run oil-fired boilers. However, it seems reasonable to assume that a large proportion of the industries will be able to generate their own low grade heat through recovery techniques such as the installation of heat recuperators, heat regenerators and thermal wheels which would be more cost effective than solar heating systems.

The impact that solar energy can make in the industrial sector is very difficult to establish, as statistics are very hard to come by. The majority of U.K. industrial energy statistics are based on a survey of industrial demand carried out by Gerald Leach and his colleagues [1]. This is based on government data collected in 1976. Since then, industrial output has substantially changed, in particular the 'energy hungry' iron and steel industries, ship building, motor manufacturing, textiles and paper making, have experienced declining levels of output, and lighter industries have expanded, resulting in a larger proportion of demand for low grade heat and so enhancing the prospects for solar energy.

The largest drawback to investment in solar energy in industry compared to dwellings, is the faster returns of

investment required by the industrial sector than by the domestic sector [10]. Quick return is something that solar energy does not offer easily. One manifestation of this is that few industrial units have double glazing. Similar arguments apply to the commercial sector.

The agricultural sector in the U.K. only uses 1.2% (73.2 PJ) of all delivered energy. But 30% of this is for space heating of rural animal houses, greenhouses and crop drying. These applications are particularly suited for solar air heated collectors, as only a few degrees temperature rise in air are often required, and so cheap solar air systems can be used.

Predicting the future demand of low grade heat is as difficult as predicting the supply because so much is dependent on political decisions. However, two contrasting predictions for the year 2025 are shown in Figure 2.1. IIED predicts a decrease by half of the total low grade heat demand while EP39 predicts an increase by half.

2.1.3 Solar supply

The sun behaves as a black body at about 5800 K emitting radiation with maximum intensity at wavelength λ_{\max} near 0.5 μm . The flux density at the mean distance of the Earth from the Sun is called the solar constant (1.353 k W m^{-2}). This has a $\pm 3.4\%$ variation due to the annual variation in solar

distance arising from orbital eccentricity. Radiation received at ground level is reduced in intensity due to a variety of scattering and absorption processes - see Figure 2.6.

On the Earth's surface problems arise with variation with time of solar energy, diurnally caused by the rotation of the Earth about its axis, and annually as a result of its orbital motion about the Sun, causing seasonal variations of between ten and thirty fold across the U.K. as shown in Figure 2.7. Meteorological changes cause variations in total annual insolation by less than 25% in the U.K. over 25 year periods. But large minute by minute changes occur because of clouds and variations in atmospheric conditions.

The amount of solar energy received on the Earth's surface is dependent on the location of the site. In the U.K. a representative annual average value for insolation on a horizontal surface bearing in mind the population distribution, is 116 Wm^{-2} , with a variation of +10% for Cornwall and -20% for the Shetlands (see Figure 2.7). For a south facing vertical surface, the average goes up to 136 Wm^{-2} . Note that these figures are for direct plus diffuse radiation, direct being solar radiation received from the Sun without change of direction, and diffuse that which had its direction changed by reflection and scattering in the atmosphere. There are three main sources of this directional change, each with its own angular dispersion. The three are

clouds, haze, and Rayleigh scattering from gas molecules. In the U.K. more than half the total insolation is diffuse (at Kew 57%). Atmospheric conditions also contribute to spatial variations. The clarity of the atmosphere today is greater in the west than in the east, contributing to a larger average solar flux in the west, Figure 2.8. This is because of industrial and urban pollution in the U.K. and polluted continental airstreams.

2.1.4 The need for storage

If solar energy is to meet the demand for low grade heat, both diurnal and interseasonal storage is required. Only approximately 53% of the annual heat consumption of likely future housing (2025), can be met directly by collectors or via the short term storage of a domestic hot water cylinder [11]. The remaining 47% has to be seasonally stored or provided by back-up heating, which is expensive. The exact proportion is dependent on the house design.

Large cost savings can be achieved by designing grouped solar heating systems for the domestic sector [12], [13]. This is so for the following reasons.

- (1) Heat storage is a major cost in solar heating. For an equivalent storage capacity a small number of large stores is cheaper than a large number of small stores.

- (ii) Heat losses from one large heat store will be less than those from a number of smaller stores with the same total volume and the same u-value.
- (iii) The total heat load from a group of houses is more predictable and less peaky due to averaging effects. Thus, the heating system does not need to be designed for the most 'energy hungry' user but needs only to be designed for the average consumer (see Figure 2.3). Thus, a more efficient system performance can be achieved.
- (iv) A large communal heat store can be located in a dead space on a site, thus saving on the high cost of space inside dwellings.
- (v) There is less overall maintenance and lower total cost.
- (vi) Individual houses with a non-optimum orientation can benefit from solar heating.

The disadvantages are the extra cost of heat distribution, the extra heat losses in the distribution system, and the extra cost of metering each house. There may also be extra legal and social difficulties, for example when selling an individual house belonging to a grouped heating system.

The rest of this chapter investigates the types of storage media available for long term storage, reviews different systems for long term storage of solar energy and examines a pebble bed storage system in great detail.

2.2 A review of long term storage techniques

Desirable characteristics of a store for solar energy are

- (i) it should be capable of receiving energy at the maximum rate the collector can provide;
- (ii) it should be able to store the maximum required energy;
- (iii) it should be capable of discharging energy at the maximum anticipated rate without needing excessive energy to extract the energy;
- (iv) it should have small energy losses;
- (v) it should be capable of a large number of charge/discharge cycles;
- (vi) it must be inexpensive.

The energy storage can be in various forms, several of which are discussed below.

2.2.1 Types of storage

Thermal Energy Storage

(a) Sensible Heat - The equation for heat stored in a specific volume of material not undergoing a phase change is:

$$Q/V = \rho c \Delta T \quad (2.1)$$

Thus the ability of a given volume of material to store sensible heat is given by ρc , where c is the specific heat capacity, usually at constant pressure, i.e. ρc_p . Other parameters of interest for storage are:

- (i) the temperature range which the material can operate over without undergoing a phase change;
- (ii) the degree to which stratification of heat can take place in the medium;
- (iii) the power requirement for addition and removal of heat to the medium;
- (iv) the type of containment required for the material;
- (v) the means of controlling thermal losses from the storage system;
- (vi) the heat losses of the system;
- (vii) the cost of the system.

Some of the above parameters are tabulated in Table 2.2 for several materials. Some of the more important materials commonly used are:

- (i) Water - This is inexpensive, readily available, has a very high volume heat capacity ($4.19 \text{ MJK}^{-1}\text{m}^{-3}$) and energy can be added and removed by transport of the storage medium itself. The disadvantages of water are that there are vast problems in containment at temperatures over 100°C , when pressure vessels are required because of its phase change to gas at normal pressure. There are also problems with containing water at temperatures below 0°C (which may happen if the store or collector is not in use) because water increases its volume when it undergoes its phase change from liquid to solid. Also there are the problems of container corrosion by warm aerated water, and that liquids require leak tight containers.
- (ii) Packed beds - These use the heat capacity of a bed of loosely packed particulate material (such as pebbles) through which a fluid is circulated to add or remove heat from the bed. The fluid is usually air although experiments with water are being carried out in France [14]. Desirable features of the particulate material are that the heat transfer coefficient between the fluid and the solid is high and the flow resistivity of

the bed is low with respect to the fluid. Normally rocks or pebbles of size 1 to 5 cm are used. If the pebbles are much smaller than 1 cm, then they impede airflow and require higher power fans. If they are much larger than 5 cm, the time to inject and remove heat increases (heat transfer equations for such systems are given in Duffie and Beckman [15]). Pebble stores have the disadvantage over water stores of having a smaller volume heat capacity (at best $3.0 \text{ MJ } ^\circ\text{C}^{-1} \text{ m}^{-3}$), requiring a larger volume to store the same energy for the same temperature rise. However they can be operated over a much larger temperature range which can partly offset this disadvantage. Also air systems are subject to less corrosion. Iron shot or iron oxide can improve the volume heat capacity and taconite spherules ready for smelting are supposed to be ideal [16]. Work is presently being undertaken on thermal storage using alumina spheres for a packed bed [17].

- (iii) Solar ponds - These are a special type of combined store and collector consisting of water 1 to 2 metres deep in a black bottomed tank. The surface water is pure and the concentration of a dissolved salt such as sodium chloride increases with depth causing an increase in liquid density, which prevents thermal convection. Solar radiation heats the bottom surface and hence the lower layer of brine where only a limited amount of convection takes place because of the high

density gradient. The poor thermal conductivity and low infra-red transmittance of the overlying brine reduces heat loss greatly and temperatures in the range 70 to 90° C have been measured in the lower layers of solar ponds in Israel. The ability to do without collectors keeps the cost of such a system down.

Problems arise in maintaining the salt gradient under the influence of the wind and keeping the pool optically clear. This can be aided by covering the pond with a transparent plastic sheet to reduce surface waves and heat loss. Leaks of brine from the solar pond need to be safeguarded against as this can cause environmental pollution. But solar ponds look very promising for certain low temperature applications where land space is not at a premium. More work is required to calculate the potential in the U.K. of solar ponds.

(b) Phase-Change Energy Storage - Materials that undergo a change of phase from solid to liquid in a suitable temperature range can be useful for energy storage if:

- (i) the phase change is associated with a high specific enthalpy;
- (ii) the phase change is reversible through a large number of cycles;

- (iii) the material can be easily contained;
- (iv) heat can be transferred through the material easily;
- (v) the cost of the material and its container is reasonable;
- (vi) the phase change occurs with limited supercooling.

A large number of materials are being investigated at present to find which fulfill the above criteria. The earliest phase change material to be studied experimentally for house heating application is Glauber's salt ($\text{Na}_2\text{SO}_4 \cdot 10 \text{H}_2\text{O}$) which changes phase at 32°C with an enthalpy of fusion of 243 kJ kg^{-1} . With repeated heating and cooling the material degrades, resulting in a reduction of thermal capacity.

One type of material of particular interest at present is salt eutectics which offer the possibility of lowering the temperature of a phase change to below the normal melting point of any of the compounds forming it. One attractive possibility is Aluminium Chloride (Al_2Cl_6) eutectic with common salt NaCl . This would, however, have to be encapsulated as it is volatile and sublimes. Problems with salt eutectic materials are that they must be contained in such a way that heat can be transferred to and from the material with a minimum temperature drop. This is usually

done by placing the material in relatively small containers and circulating air around them. Problems arise with heat transfer, because though when the solid is heated it liquifies first at the walls and then inward towards the centre of the container, as heat is extracted crystallization will occur at the walls and then progressively inward, increasing the thermal resistance to heat transfer, which is dependent on the degree of solidification. Other problems with phase change materials are their corrosiveness, vapour pressure and toxicity.

Some phase change salts have reached the state of development where they are now coming onto the market; one such material is calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$). The phase change temperature is 20.8°C and it has a storage capacity of 263 MJ m^{-3} at the phase change. It costs about $\pounds 2,500 \text{ m}^{-3}$ compared to $\pounds 10 \text{ m}^{-3}$ for pebbles. A list of further phase change materials and their phase change temperatures and enthalpies can be found in references [18] and [19].

Alternatives to thermal storage

(a) Electrical Systems - Solar cells produce electrical energy (at an efficiency of 5 to 25%) that can be stored in electric batteries. Present possibilities include lead acid, nickel-cadmium and nickel-iron batteries. The efficiencies (ratio of electrical energy output to electrical energy input) of these batteries range from 60 to 80% [20].

(b) Biological Systems - Energy stored in the form of crops is one of the earliest forms of interseasonal storage but its use is rather limited [21] with bioconversion only 1% efficient (ratio of stored energy to annual incoming solar radiation, so this is combined storage and collection efficiency).

(c) Thermochemical Storage Systems - This type of storage involves the release or absorption of large quantities of heat during chemical reactions.

The sulphuric acid heat pump consists of two separate chambers of water and sulphuric acid connected by a vacuum line. When heating is required, a valve is opened allowing water vapour to pass into the acid chamber. Heat generated in the ensuing chemical reaction, i.e. 'heat of solution', is removed using a heat exchanger. When energy is to be stored the dilute sulphuric acid solution is concentrated by using energy to break the $\text{H}_2\text{SO}_4 - \text{H}_2\text{O}$ chemical bond therefore releasing water from the solution. The water vapour is then condensed by a heat sink at the water chamber providing storage in the form of heat of "de-solution". The system is complex but allows great possibilities with energy densities of 1 GJ m^{-3} [22]. But this method has not been made cost-effective [23]. More recently chemical heat pumps using anhydrous sodium sulphide and water have been investigated and appear to be more promising [21].

2.2.2 A review of communal interseasonal storage systems of solar energy

Many examples of solar energy systems utilizing short term storage have been designed and monitored in the U.K. Such systems are cycled 100 to 200 times a year, whereas interseasonal stores are only cycled once per year. This makes the use of elaborate or expensive storage media, such as phase changes, chemical or electrical storage, difficult to justify for interseasonal storage. Since interseasonal storage only becomes feasible for large stores a large capital expenditure is required for demonstration schemes. So far, funds have not been available for such a scheme in the U.K. The substantial body of knowledge developed for short term storage for single residences does not carry over to larger systems with communal interseasonal storage. For example (i) stationary south facing collectors are clearly the best for short term storage, but are not necessarily best for summer collection at high latitudes where days are long and where the solar azimuth angle varies over a much wider range. (ii) For short term storage stratification is clearly advantageous because the thermal losses from the store do not dominate performance. But it is possible that large interseasonal storage tanks buried in the ground could suffer adversely from extensive stratification where the top of the tank (at the highest temperature) is exposed to the lowest ground temperature. (iii) The temperature ranges and the

temperature differences between collector and ambient temperatures in operation of seasonal storage systems may be different from diurnal systems, dictating that the collector design may also be different. So, practical operational experience with interseasonal stores is essential.

Only two demonstrational schemes of interseasonal storage of solar energy exist to date in the U.K. The National Centre for Alternative Technology has built a storage system which meets the annual space heating demands of its exhibition hall. Heat is supplied from 100 m² of roof mounted trickle collectors to a sunken 100 m³ store [24]. Because the store was situated in a slate quarry and heated an exhibition hall, the small amount of data collected had little general applicability. This project was privately funded. The one government funded interseasonal heat store is attached to a single house at the Building Research Establishment near Watford. The house is poorly situated and as a consequence required massive heat storage tanks which were completely uneconomic.

Several interseasonal storage systems have been constructed throughout Europe and the U.S.A., and in particular in Sweden. These utilise various storage materials, collectors, and configurations.

Water stores

Sweden established a major programme of research and development into interseasonal storage in 1977, with six district heating schemes under construction by 1981 [25]. The oldest of these is at Studsvik, 100 km south of Stockholm, where 500 m² of office area is heated by 1209 m² of compound parabolic collectors, mounted on a floating rotating lid of a store [26]. The heat is stored in 640 m³ of water in an insulated pit, as shown in Figure 2.9. The system was initiated in December '77 and completed in February '79. The main problem during construction of the store was a failure of the rubber liner which occurred after the tank had been filled. The system has now been operating for some five years and has shown itself to be reliable (97% plant availability in 1980) and running very much according to plan, providing almost 100% of the energy demand for the office building and with the collectors providing 90% of the initially expected energy. The collectors run without antifreeze and so operate only between April and October, however, little solar energy is lost at this high latitude (60° N). Mounting the collector on top of the store allows azimuth tracking which increases the energy collected during the long summer days by 48% while only using 270 watts for the complete tracking system. This type of energy collection would be less of a benefit in the U.K. where more energy is diffuse and where, because of the low latitude, more energy falls in the winter. The store temperature fluctuates

between 30 and 70° C, with 30° C being the minimum water distribution temperature. Water distribution is via flexible plastic piping, which costs half that of conventional piping.

A breakdown of the costs of the system is

| | |
|-----------------------------|-----|
| Heat store | 21% |
| Solar collectors | 51% |
| Heat pump and central plant | 15% |
| Distribution system | 13% |

The estimated cost of a similar system providing 93% of the heat for 400 houses, each with a heating load of 54 GJ per annum, is £5,150 (1981) per house [27].

The Lambohov project in Linköping about 200 Km south west of Stockholm, is the first large-scale application of many of the techniques initially developed in the Studsvik project. The goal of the project was to provide 100% space heating and hot water for 56 terraced houses, some 93% coming from solar energy in the first year of operation before being fully charged, the balance as electricity largely to drive heat pumps. The solar energy is collected via 3045 m² of flat plate collectors with selective absorbers mounted on the house roofs. Hot water from the collectors is fed into a 10,000 m³ water tank clad in insulation and buried in the ground. The system was fully operational in May 1980. The total system cost was ~ £27,000 (1981) per house [28]. A breakdown of the system costs is

| | |
|------------------|-----|
| Heat store | 35% |
| Solar collectors | 24% |

| | |
|---------------------------|-----|
| Heat pump, central plant, | |
| planning and management | 36% |
| Distribution system | 5% |

The Inglestad project located near Vaxjo in Sweden is based on the same principle as the two previous projects. However it is designed for much higher temperatures of solar collection, storage and end use. It is to meet 50% of the total energy requirement of 52 detached houses. The solar energy is collected in 1,300 m² of tracking parabolic concentrating collectors which can provide pressurised water at temperatures up to 105° C. The water store, which is situated above ground, has a volume of 5057 m³, and the tank is made of insulated concrete to withstand the high storage temperature (95° C), this helps to keep the store volume small. The house heating system is designed to operate with a supply temperature of 80° C, and return temperature of 50° C. The capital cost per house for the scheme is £19,320 (1981) [29]. The breakdown of costs is as follows

| | |
|---------------------|-----|
| Storage | 33% |
| Solar collectors | 28% |
| Distribution system | 8% |
| Others | 31% |

This project has not been entirely successful, as a result of the higher temperatures. The expense of the system is attributed to concrete tank and concentrating collectors required to reach the high operating temperature.

The Lyckebo project located near Uppsala 40 miles north of Stockholm is Sweden's largest planned solar district heating scheme. It is planned to supply 500 houses with 100% solar heating. This has been designed to utilise 20,000 m² of high performance flat plate solar collectors, some situated on the ground, others on buildings. The required water heat store size is 100,000 m³ and is to be based in a rock cavern, blasted in 1981. Total cost of the system per house is envisaged as £10,500 (1981) [29]. The breakdown of costs is as follows

| | |
|------------------|-----|
| Storage | 23% |
| Solar collectors | 38% |
| Distribution | 16% |
| Others | 23% |

The Lyckebo project is about twice as expensive as a conventional district heating project in Sweden. Other similar projects are now being considered for up to 2,000 houses.

Although Swedish research and development is the most advanced for water storage, similar systems to the Studsvik program had been developed in the U.S.A. as early as 1975 and to date some three small-scale prototypes of the 'azimuth-tracking floating concentrator on a seasonal heat storage reservoir' have been constructed at the University of Arizona [30]. Computer simulations have been carried out based on the results to determine store sizes for 10, 50 and 200

houses. No full scale system has yet been constructed. Estimated net cost per house for a hypothetical system in Tuscon, Arizona, heating 250 houses is £3,020 (1981). Work in Germany [31] and Italy [32] has also been undertaken to design and construct interseasonal water stores, but for individual houses at mid-latitudes, where the mismatch between supply and demand is not as severe as in the higher latitude U.K.

Earth stores

More recently, work has been carried out in Europe on using the earth as a storage medium.

In Switzerland a 240 m³ heat store has been constucted of rubber tubing buried in wet earth placed inside a plastic bag then buried in the ground with a layer of insulation on top [33]. The store depends on having surrounding dry soil to insulate the sides. No costings are available.

In Finland a combined solar heating and heat pump system with a seasonal heat store of a water filled rock cavern and surrounding rock (see Figure 2.10), is used in the Kerava solar village to heat 44 flats. The total cost of the system exceeds that of an average system by approximately 35% [34]. A sensitivity analysis of the system showed that a small improvement in the collector performance would be more beneficial than a small increase in the collector area or

storage volume.

The Netherlands have concentrated their research on earth storage. In Gronigen, TNO Delft are constructing a 23,000 m³ store consisting of water-saturated sandy soil, with a heat capacity sufficient to serve 96 well insulated houses (annual space heating and hot water load 44 GJ per house) [35]. The store has plastic tubing buried to act as a heat exchanger and also a 100 m³ short term water storage reservoir, Figure 2.11. The store is 1 metre below the surface with a layer of insulation on the top and some 20 m deep. No side insulation is required as horizontal ground water movement is low.

Vertical ground water movement caused by locally heated soil is obstructed by an impermeable clay layer. The store is to be heated by 25 m² of Phillips evacuated tube collectors mounted onto the south facing roof of each house. System costs are not yet available, however the storage costs are of the order of £13/m³ (1983) and the storage system has performed very much to expectation. Design studies for similar systems have been carried out in France [36].

Most recently a large amount of interest in Sweden has developed in an earth storage system for low grade heat 'Sunstore' [37], see Figure 2.12. The most prominent feature of the system is the low temperatures (< 35° C) throughout the system. This is advantageous because the storage heat loss is less and collectors operate more efficiently at lower temperatures and nearly all types of collectors have the same

efficiency at low temperatures so the cheapest collectors can be used. However larger quantities of fluid must be transported to achieve the same energy transfer. Hence, larger pipe diameters are employed to achieve high flow rates without incurring the penalty of excessive pumping power. Cheaper materials such as plastics can however be used for the pipework due to the lower temperatures. Because of the lower temperature the heaters inside the house need to be of a larger area, so all the floor and ceiling areas are used as heat emitters. This does however have the advantage of providing a more comfortable room interior as the surfaces of the room do not have extreme temperature differences. The cost of a 'Sunstore' system is dependent on soil type but it does appear very competitive with other interseasonal heating systems ($\approx 1/2$ price). Particular caution should be taken in utilizing results from Swedish underground heat storage as Sweden has extremely good conditions for this type of storage, thanks to its particular type of glacially formed geology and near-surface crystalline bedrock. More work is needed on the use of ground storage of low grade heat in the U.K.

Aquifer storage

Aquifer are naturally occurring subsurface strata of water-bearing sand, gravel or porous rock. They are commonly sedimentary layers, although fissured igneous and metamorphic rocks may contain sufficient water for thermal energy

storage.

In Paris ARMINES are planning to heat 224 apartments using the Ypresian aquifer which lies about 80 m under the northern part of the town. During the summer the aquifer is charged up using solar collectors, and energy is extracted in winter with heat pumps. A total of 1,300 m² of unglazed collectors is used to heat the aquifer from its normal temperature of 13° C. The total cost per apartment is £1,600 (1981) giving a payback period of less than 10 years [38]. This type of system is however very site specific.

Solar ponds

Solar ponds have been considered for interseasonal storage in the U.S.A. for areas with climates similar to that experienced in the U.K. [39]. Results from these feasibility studies have shown that to enable the solar pond to store sufficient energy from the summer to the winter the pond needs to be of the order of 8 metres deep. The cost of salt for such a large non convective region would make it prohibitively expensive, so only the top layer of these stores would contain brine and so act as an insulating layer. The rest of the store would be pure water and so would convect. The mixing of these two regions would be prevented by a transparent partition. A feasibility study for the North American town of Northampton, Massachusetts, which has a population of 30,000 and a population density of 3,700

people per square mile, concluded that the cost per house would be £6,000 (1980).

Research in the U.K. on solar ponds has concentrated at the University of Sussex where a 5 metre diameter experimental pond has been constructed and is to be followed by a 150-200 m² pond. Feasibility studies have indicated that by using commercially available materials, the cost of a pond to serve a group of 100 houses would be in the order of £10,000 (1982) per house [38], and that the minimum cost of energy from a solar pond would be £20 (1984) per GJ for a 1,000 house scheme. This is assuming the cost per square metre for a raw site is £55 m⁻², so for a house requiring 53 GJ per annum space heating, 17.5 m² per house of solar pond would be required.

U.K. Feasibility studies

No full scale demonstration projects for interseasonal storage of solar energy have been carried out in the U.K., but several feasibility studies have been carried out.

The City University, London, has performed a theoretical investigation of interseasonal solar energy storage in the ground [40]. The results showed that if 100 houses (annual heat consumption 46.8 GJ per annum per house) were heated by 5,851 m² of solar collectors ($U_L = 6.0 \text{ W m}^{-2} \text{ K}^{-1}$) would provide 78% of the annual load for a cost of £4,000 (1982) per house. The investigation concluded that the variation of

soil properties would not greatly affect the auxiliary energy required, provided that the site were above the water table throughout the year. Low loss collectors are important in reducing the auxiliary energy input, rather than increased collector area.

The University of Sheffield has carried out a preliminary feasibility study into the use of solar energy to provide year-round heating for a factory unit, [41]. The system combines a water store below the factory unit (floor area 972 m²), solar collectors on the roof and a heat pump. The capital cost is an extra £6,000 (1978) when compared to a normal oil fired heating system. This enables 75% of the annual heating and hot water load (480 GJ) to be met by solar energy.

Earth Resources Research (ERR) has investigated the potential for solar district heating utilizing a communal water store to meet the future demand for domestic heating in the U.K. The systems investigated are based on the results from Swedish schemes with roof mounted evacuated tube collectors, a local heat distribution network and a water-based seasonal heat storage tank made of reinforced cement-mortar construction and buried in the ground. The system is designed to provide 100% of the space and water heating for 300 houses with 4,600 m² of collector and 17,700 m³ of water store. The cost per house is £2,416 (1981) [11], (section 2.4 presents a breakdown of the costs). These figures are

based on the costs in countries where the system components are freely available and so are dependent on a large indigenous industry. The calculations performed to design the system were very rough and more sophisticated modelling of this system is required to take into account the difference in climate between Sweden and the U.K. (the U.K. has a smaller summer to winter variation in solar radiation), and in heat load (the Swedes have a higher internal temperature, lower external temperatures, but better insulated houses).

The Polytechnic of Central London (PCL) has also examined the possibility of interseasonal storage of solar energy. They have adopted a computer model which compares the operation of the PCL Solar House at Milton Keynes [42], to that of a group of houses heated by an interseasonal water store. The system consists of $2,100 \text{ m}^2$ of flat plate selective collectors mounted on a group of 50 houses heating a $7,500 \text{ m}^3$ water store for a total capital expenditure of £5,480 (1980) per house [13].

Table 2.8 summarises the data reviewed in this section on domestic communal storage systems. The cost per house varies from £2,500 to £30,000. The difference in cost can be attributed to the size, location and type of system examined. The items included in the costing also varies. Some include labour, land and a large market for the system, while others do not. The most expensive systems appear to be those which

have actually been constructed and so are 'real' costs. However these are often high because of the experimental nature of the project.

Most recent results suggest that lower storage temperatures produce lower costs, though the evidence is far from conclusive for the U.K. Therefore detailed modelling is required of the performance and economics of the different collection and storage systems under U.K. conditions.

2.3 Prometheus

When work on this thesis first started (1979) no serious work had been done in the U.K. on interseasonal storage of solar energy. Sweden was investigating storage and collection systems utilizing water as the heat transfer fluid. So it was decided at the Open University to investigate the possibilities of using air as the working fluid and a pebble bed for the storage medium of a communal interseasonal solar system in the U.K. (Prometheus). Although a pebble bed has a lower heat capacity per unit volume it does offer the advantage of possible higher storage temperatures and stratification which results in a smaller store. It was therefore decided to investigate the cost effectiveness in terms of money and energy of this type of system in the U.K. The work reported in section 2.2.2 which has been carried out since 1974 now suggests that lower rather than higher temperatures are probably more appropriate for interseasonal storage.

2.3.1 System description

Prometheus is a combined collector and interseasonal store initially outlined by B.W. Jones of the Open University [43]. The original design of the system which could heat 200 low energy loss houses all the year around, was a pebble bed store in a canal-like structure which would run at the bottom of a row of gardens between two rows of houses, see figure

2.13. The pebble bed is 280 m long, 10 m wide and 4m deep, with the collectors mounted above the store, Figure 2.14.

The important design features of Prometheus were originally considered to be:

(i) that Prometheus could meet 100% of the annual space heating and hot water energy demands of a house, thereby eliminating the need for a backup system;

(ii) high temperatures in the store at the end of summer
(a) to enable heat to be delivered at temperatures above 80° C

(b) to keep the store volume and so cost down.

The storage medium chosen for such high temperatures is pebbles with air as the distribution fluid. Both are cheap and readily available, with no serious containment and distribution problems;

(iii) a flat plate evacuated collector with air as the heat exchange medium, feeding the heat into the store, to feed the store with temperatures in the 100 to 200° C range and at the same time keeping the collector area and so space and visual attraction to a minimum, while also keeping costs to a reasonable value. Flat plate collectors of very high efficiency are required.

(iv) location of the collector on top of the store

- (a) to reduce transmission losses at high temperature and still reduce the cost of the collector and store, the same insulation being used to back the collector and to top the store;
 - (b) to avoid locating the collectors on the house which for new houses limits their design and orientation, and which for existing houses (which will form most of the housing stock for decades to come) is very difficult;
 - (c) to have central maintenance of the collectors (e.g. snow and dust removed, repairs), which is more convenient for maintenance staff and householders, and less costly and safer as the risk of falls from heights is avoided (a factor which may make solar energy more hazardous than nuclear!);
 - (d) to attain far more effective fluid temperature control. If the ductwork between the store and collector is small then so will be its thermal mass, so even short periods of sunshine can be utilized;
 - (e) to attain an economy of scale by building larger collectors or series of collectors;
- (v) a communal store, to reduce insulation costs and to eliminate the variation of user demand explained in section 2.1.2 and so avoid over capacity by designing for the most 'energy hungry consumer';

(vi) a store below ground with the collectors horizontal to provide an aesthetically pleasing system. Originally it was intended to place water on top of the collector to make the system look like a canal and to reduce the transmission losses through the cover, this was however ruled out because of dirt. The collectors were situated at the bottom of the garden to prevent the houses from overshadowing them.

2.3.2 Proto-Prometheus

A very small prototype (see Figure 2.15 and Plate 2.1) was constructed to help us establish the practical problems in constructing a larger system. The system was designed to enable the monitoring of both the collector and the store. Temperatures were measured within the collector, store, store insulation and in the surrounding ground. Wherever possible the testing was designed to meet the standards set by the Commission of the European Communities [44] for the collector and the ASHRAE standard [45] for the store. Subsequently the ASHRAE storage standard has been found to not account for realistic cycling of the storage system [46].

Because of lack of funds the system was constructed on a much smaller scale than would provide interseasonal storage and was built with materials and monitoring equipment which were old and not ideally suited to their application. As a consequence the results obtained were rather limited.

Results were only obtained with a collector made with a selective absorber ('Maxorb') and with air between the absorber and cover. The measured collector parameters in situ were $U_L = 4 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ and $F' = 0.7$ (for an explanation of symbols see Chapter 4).

Figure 2.16 shows the insolation incident on the collector on 28th September 1981. Figure 2.17 shows the response of the collector and store to the variation in insolation, also plotted is the ambient temperature. Until 10 AM the system is stagnant (fan off) and the collector shielded from solar radiation by placing an opaque sheet on overnight so the system temperature is only dependent on the ambient temperature. At 10 AM the collector is uncovered but the fan is still left off. At 12 noon the fan is switched on, and produces a flow rate of 22 Kg hr^{-1} . Figure 2.18 shows the distribution of temperatures within the system at 14:25 hours on the 22nd September 1984.

Problems which occurred with the system did provide some useful experience and valuable information for any such future construction:

- (i) Constructing such a test device outside is a very costly and labour intensive operation with the weather nearly always a problem.
- (ii) The store base was below the level of the local water

table. This meant that the brick exterior of the store had to be rendered with waterproof cement. This proved to be inadequate in preventing water penetration of the store insulation. So the store had to be pumped and the insulation sealed in waterproof containers. When the water table level rose the insulation was observed to float. Construction above ground would avoid problems with a watertable but make the store more visually obtrusive.

- (iii) A steel tank was the only available store container. Had stratification taken place in the store this would have been a serious short circuit. Only limited stratification was monitored.
- (iv) Mass flow rate measurements were carried out with a pitot tube, this was found unsatisfactory because of the complex calibration. Orifice plates were subsequently used.
- (v) Using old, faulty data loggers is more trouble than it's worth. In subsequent work new Microdata M1600 data loggers were used.
- (vi) Thermocouples were used for measuring collector and store temperatures. These were found to be very troublesome in the outdoor environment, in particular

with problems associated with connections. Thermistors were less trouble. However, platinum resistance thermometers were subsequently used because they gave a more linear response than thermistors, they were found to be of greater accuracy, and gave fewer connection problems than did thermocouples.

- (vii) Temperature rises within the store and collector were found to be asymmetrical, see figure 2.18. This suggests that the air flow behind the collector and within the store was not uniform. A better designed manifold air inlet into the collector and more uniform packing of the pebble-bed store could be the solution to these problems. However, considerable effort was made to grade the pebbles uniformly within the store, because of the large variation in sizes when delivered from the local quarry, although the quarry had already graded them. Grading and washing was carried out at the Open University by hand and with a 2 cm grating. After grading the pebbles, the average diameter was measured by filling a bucket with a sample of pebbles, and was 2.6 cm, and the void fraction was 0.39, measured as suggested by Duffie and Beckman [47]. To obtain some indication of the distribution of pebble sizes within the sample the maximum and minimum dimensions of each pebble were measured for a sample of 204 pebbles. The results are plotted in figures 2.19 and 2.20. From

this a shape factor, s , can be calculated. This can be defined as the average minimum dimension divided by the average maximum dimension. For the pebbles used in proto-Prometheus (see Plate 2.2) the shape factor was measured to be 0.42. It is suggested that similar shape factors are recorded whenever pebble bed stores are constructed for scientific investigation, as the shape factor will affect how the store packs.

The specific heat capacity of the pebble bed was measured as $1,110 \pm 140 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$ by immersing a sample of pebbles in a heated water bath and comparing the temperature rise of the bath for a given energy input, with and without the pebbles. The measured specific heat capacity compares favourably with the value of $1,130 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$ quoted by Kreith and Kreider [48] for sand and gravel.

- (viii) For cheapness and convenience in construction, standard 2" copper pipe was used for the ducts. However this caused unduly large pressure drops within the system. Pre-insulated larger diameter (> 10 cm) plastic flexible piping is now more standard in the U.K. and is recommended for future use.
- (ix) The store temperature was found to fluctuate in sympathy with the ambient temperature, with the

system stagnating, see Figure 2.21. One explanation for the cooling of the store at night time is the natural circulation of hotter air from the store to the cooler collectors, since there were no dampers between the collector and store. Subsequent calculations proved that this could be the case. However the rise in temperature during the day time is more difficult to explain as the convection would have had to take place in a downward direction. It is suggested that all future systems utilize a damper system to prevent any air circulation during stagnation. Similar problems have been reported for water systems and non-return water valves are used but these can create air-locks [69].

As a result of constructing and operating the prototype it was felt that not enough was known about the operation of pebble bed stores and of air collectors as separate entities. This led to the separate investigation of pebble beds and air collectors under more controlled conditions in the laboratory. The development of an efficient air collector is explained in Chapter 6; this work in turn led to a detailed investigation of air collector testing - see Chapters 4 and 5. Work on the operation of a pebble bed store is now being carried out by a research student at the Open University, in particular to determine the parameters which affect destratification [49].

2.3.3 Performance Modelling

The original design study of Prometheus performed by B.W. Jones [43] involved a simple performance model. However subsequent work on the design and operation of collectors has led to more sophisticated and realistic modelling of Prometheus.

The performance of active solar heat systems with interseasonal storage is more difficult to predict than short term storage systems because fewer systems are in operation, thereby obviating an empirical relationship similar to the f-chart method [47] (see Chapter 3). Also, the large scale of these projects allows the use of more novel collectors which do not fall into such a narrow range of standard parameters as the conventional domestic hot water roof top collectors. The problem is even more acute for a long term pebble bed storage system, because the long term operation of pebble bed stores is not fully understood. This means that a theoretical technique with several simplifying assumptions must be used. However results from such models provide useful information to a first order approximation and suggest whether systems are worthy of further more detailed investigation.

Lunde [50] has developed an analytic technique for obtaining the performance of a solar system with long-term storage. The store is assumed to have a uniform temperature

throughout, i.e. no stratification, and to be large enough so that the variation in store temperature over a period of a month can be regarded as linear.

The nett heat transferred to storage, Q_N , during the entire monthly period t_m is given by the following equations:

$$\begin{aligned} Q_N &= \text{solar energy collected} - \text{storage losses} - \text{demand} \\ &= Q_T - L_s - L \end{aligned} \quad (2.2)$$

The loss from the storage tank during the month is:

$$L_s = U_s A_s (T_s - T_g) t_m \quad (2.3)$$

The integrated collector equation gives the solar energy collected during the month in terms of the parameters relating to the solar collector (F_R , U_L and $\tau\alpha$, see Chapter 4).

$$Q_T = A_c F_R [(\tau\alpha) E_T - U_L (\bar{T}_s - T_{at}) t_t] \quad (2.4)$$

The monthly average store temperature is:

$$\bar{T}_s = T_{s0} + Q_N / 2MC \quad (2.5)$$

Substituting eqns. 2.3, 2.4 and 2.5 into eqn. 2.2 and solving for Q_N gives:

$$Q_N = \frac{A_c F_R [(\tau\alpha) E_T - U_L (T_{s0} - T_{at}) t_t] - L - U_s A_s (T_{s0} - T_g) t_m}{1 + \frac{A_c F_R U_L t_t + U_s A_s t_m}{2MC}}$$

The next task is to evaluate E_T , T_{at} and t_t , which all refer to the time during the month for which the solar irradiance is above the threshold value, I_{th} , required for a useful transfer of heat to the store. I_{th} is given by:

$$I_{th} = \frac{U_L}{(\tau\alpha)} (T_s - T_a) \quad (2.7)$$

In this equation, T_s and T_a are hourly averages within a particular month such that the values at the n th hour on any day in the month are the same as the n th hour on any other day in the same month. This typical day is called the month-day. It is assumed that a monthly average for τ_a (i.e. $\overline{\tau_a}$) can be used. Thus I_{th} also corresponds to the n th hour on the month-day.

To evaluate E_T , T_{at} and t_t , the first step is to set T_s equal to T_{s0} on 1 March. The value adopted is 30° C. Equation 2.7 is then used to calculate I_{th} for the first daylight hour on the March month-day. If the tabulated irradiance I is greater than I_{th} then the collector is assumed to have been on for that hour. The time t_t is increased by 3600 s (1 h), E_T is increased by 3600 I , and T_a is recorded so that T_{at} may be obtained for March. This is repeated for the next daylight hour, and so on until nightfall at the end of the month-day, and thus E_T , T_{at} and t_t are obtained for the month of March. Q_N is then obtained for March from eqn. 2.6. The store temperature at the beginning of April is then obtained from

$$T_{s0} (\text{April}) = T_{s0} (\text{March}) + Q_N / 2MC \quad (2.8)$$

This procedure is then repeated for April, May, etc.

If the store temperature becomes less than 30° C, auxiliary heat is fed into the store to keep it at 30° C.

A computer model 'Sunstore' (see Appendix A for computer listing) was written to calculate the percentage of useful energy produced by a Prometheus type system, see Table 2.3

for system description. The program was run on a Hewlett-Packard 86 microcomputer using solar radiation data from Kew; monthly averages of hourly radiation on a horizontal surface 1966 to 1975, and average temperature data from London Airport, Heathrow 1971 to 1980. The model was used to investigate the useful energy that Prometheus could supply to type A1 houses, that is, a new 3 bedroom house constructed to meet 1975 Building Regulations and oriented north south (see Chapter 3 for a detailed description of house types), and for a house built to a better standard of insulation, type A5. The results from using this model are presented below.

The monthly energy demand for a type A1 house is shown in Figure 2.22 along with the energy supplied by a basic Prometheus as described in Table 2.3, 69% of the annual heating and hot water demand was supplied by Prometheus. This was mostly during the spring, summer and autumn. Note that in the original design study of the system by B.W. Jones [44] it was estimated that such a system would provide 100% of the annual energy. The reduction is partly because more realistic (higher) U-values have been assumed in my model.

The effect of changing the collector overall heat loss coefficient is shown in Figure 2.23. A large increase in system efficiency results from a reduction in collector heat loss. This is not only because the collectors operate with a higher efficiency but also because they can capture solar energy at times when less efficient collectors cannot.

Similar conclusions have been reached in Finland where the interseasonal mismatch between solar energy and domestic heating demand is greater and the radiation is more diffuse. The cost of an interseasonal system utilizing high performance concentrating collectors (parabolic trough with a concentration ratio of 10) is half that of a system using flat plate collectors, and only half the water storage volume is required [51]. It is for these reasons that methods of reducing the collector top loss to increase the performance are investigated in Chapter 6.

Figure 2.24 shows the effect of changing the collector area while keeping the storage volume constant. Note that halving the collector heat loss has approximately the same effect as doubling the collector area.

Figure 2.25 shows the effect of varying the thickness of the tank insulation. There is little benefit in increasing the thickness of the insulation beyond 0.6 m (for an insulation thermal conductivity of $0.036 \text{ W/m}^\circ\text{C}$).

Figure 2.26 shows the effect of changing the storage volume by changing the store length. All else being constant there is little benefit in increasing the store size. The effect of changing the storage shape from an oblong to a cube was studied. The energy supplied by a basic Prometheus with a cubic store of $(22.4 \text{ m})^3$ was 75.6% (the collector area was kept the same) compared to 69% for the oblong store. This

improvement is due to the reduction in surface to volume ratio.

Figure 2.27 shows increasing the number of houses which share a cubic store increases the solar fraction. The same storage volume per house (112 m^3) and collector area per house (28 m^2) is used regardless of the number of houses sharing the store. There is little benefit in grouping more than 50 houses together in terms of the energy provided. However there may be strong economic reasons for more houses sharing the same store.

If the basic Prometheus with a cubic store is used instead to heat 100 better insulated houses (type A5) then 100% of the space and hot water energy demand could be met by solar energy. Such a system could have storage temperatures in excess of 150°C in October. Increasing the heat loss reduces the fraction of energy provided by solar more on a better insulated type A5 house than on the type A1, see Figure 2.28. Doubling the collector top loss reduces the energy supplied by solar from 100% to 74%.

From these results it is concluded that the original design of Prometheus would not provide 100% of the heat energy for a 1975 Building Regulation house. Only when well insulated houses are heated does the system provide 100% of the energy and then only with the store in a cubic configuration. Increasing the number of houses sharing the same store above

50 offers little advantage in terms of energy supplied for this particular model, as does increasing the thickness of the storage tank insulation above 0.6 m (for $k = 0.036 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$). The heat loss from the collector is clearly a critical parameter in the energy provided by Prometheus.

Note that this analysis was carried out with horizontal insolation data, as this was all that was available in a form suitable for 'Sunstore'. This means that the results only apply to horizontally mounted collectors. Tilting the collector to the south would increase the total energy collected and also reduce the seasonal storage required because proportionally more energy would be collected in the winter period when the angle of the Sun is low.

2.3.4 Economics

Economic evaluation on new energy technologies is used to assess how a system will benefit society, and success is assumed if one technology costs less than another. The problem with this type of analysis is that it has a number of shortcomings; it is not possible to determine the inflationary effects of energy price rises or costs - a very important parameter, especially in comparing an energy technology with large capital investment and low fuel costs, with one that has a small capital investment and large annual fuel running costs, as Prometheus is compared to a fossil fuel energy technology.

One convention for comparing different energy supply systems is to compare the present value of the costs (PVC) of each system. For our purpose, the present value of the costs per house (PVC_h) is conveniently written as

$$PVC_h = C_h + K_h \sum_{n=1}^N \frac{1}{(1+i)^n} + F_h \sum_{n=1}^N \left(\frac{(1+f)}{(1+i)} \right)^n + R_h \sum_{n=1}^N \frac{1}{(1+i)^n} \quad (2.9)$$

C_h is the capital expenditure at time zero (which we take to be June 1980), the associated hardware lasting for N years. K_h is capital expenditure at time zero which is repeated (in real value) at years $n_1, n_2 \dots$ less than N . F_h is the fuel cost per year at time zero, and R_h is the other running costs per year at time zero. The factor f is the differential rate of fuel inflation. Note that K_h and R_h have been given zero differential rates of inflation and so increase at the average rate of inflation. The factor i , the discount rate, represents the degree to which we value having something today more than tomorrow.

Equation 2.9 does not provide an ideal method of comparing differing technologies. It does not for example include hard to cost factors such as amenity and pollution. The answers obtained from this type of analysis are also critically dependent on the values of i and f . These parameters are to a certain extent chosen by governments and so the analysis is politically sensitive. It is also naive to think that

economic forces are the sole motivation behind peoples' investment. If this was the case then people would not have invested in double glazing nor researched into fusion energy, the payback times for both these technologies being very long. Also, equation 2.9 does not take into account the benefit a community may receive from an indigenous energy source. For example, a community without an indigenous source of fossil fuels may benefit from a communal solar heating system, because a greater proportion of the community expenditure will stay within the community. Moreover, if the solar system utilizes a large proportion of indigenous technology, then local employment will improve and cause a small but significant multiplier effect which could work to enhance the local economy.

Although the present value of the cost of a system only provides a limited amount of useful information when comparing two different technologies, it is nevertheless a useful exercise and one which various funding bodies utilize. For this reason the (PVC_h) for a Prometheus system has been compared to that of a gas fired central heating system and an electrical heating system (Economy 7). All the heating systems produce 100% of the annual hot water and space heating demand for a type A5 house. A schematic diagram of Prometheus is shown in Figure 2.29 and a detailed breakdown of the costed Prometheus in Table 2.4 as costed from Spons 1979 [52].

Table 2.5 shows the PVC_h for the three heating systems over a lifetime of 45 years ($N = 45$), this being an estimate of the hardware bought by C_h for Prometheus, subject to maintenance reflected in the running costs per year R_h . C_h for Prometheus includes the cost per house of basic hardware required for central heating (radiators etc.). This home based hardware also accounts for C_h for gas, the rest being included in K_h , which mainly represents the gas boiler, replaced every year. K_h is zero for Prometheus. This assumption is based on the fact that except for the cost of the collectors the capital cost of Prometheus is based on conventional hardware, where the reliability is high. Replacement of collectors is accounted for in R_h . All the capital cost of the electrical system is in K_h . It is assumed that hardware bought by K_h lasts 15 years, subject to any maintenance in R_h .

Doubtless one can argue that F_h , C_h , K_h and R_h could be a little different from the values listed in Table 2.5. However, the ratios of PVC_h of one system to another are not very sensitive to small changes in these factors. One can however argue for larger fractional changes in f and i . Table 2.5 shows the value of PVC_h corresponding to three sets of values of f and i , in all cases f and i being assumed independent of n . The table shows that the PVC_h ratios of one system to another vary enormously from one set to the next. The value of f of 0.04 corresponds to the prediction that fuel prices will rise in real terms by a factor of 2 to

3 over a period of 20 years up to the year 2000 [53]. However, with $N = 45$ this value of f is being extrapolated. $f = 0.02$ fits reasonably well with a recent estimate of the increase in the real price of fuels by 2025 [2]. The larger value of i (0.05) is the value currently adopted by the U.K. government for public investment in energy supply systems [2], whereas there are strong arguments [54] that i for energy systems should be zero, the lower value used.

An analysis for the systems installed on a less well insulated house shows Prometheus to be less economic [55].

From Table 2.5 we can conclude that the version of Prometheus costed cannot be ruled out on economic grounds. However the costing of a system will demand very much on local conditions. The cost of the storage medium (pebbles) accounts for 23% of the system cost. A large proportion of this cost is in transportation which is dependent on the distance to the local quarry. If the store has to be completely buried to ground level and the excavated material dumped, the cost of constructing the store increases dramatically. Slightly cheaper methods of store construction could be envisaged. However the cost of the collectors forms the largest cost component (37%) and as yet collectors of the required efficiency are not available on the market, although comparable prices have been quoted by manufacturers for large numbers of similar high performance collectors [56].

It has been argued that the economics of a Prometheus type system would improve if they were to be built in the future [13], because the price of fossil fuels would have increased but the capital cost of Prometheus would remain the same. However this is not strictly true since the capital cost of Prometheus is linked to the cost of fossil fuels, because fossil fuels are required to construct Prometheus, see section 2.3.5.

Several simplifications have been made in this analysis which would effect the results. However the combination of these simplifications is not considered to affect the general conclusions. They are however noted here for possible future refinement of the model and for the information of the reader.

- (i) The land on which the store and collectors is built has been given zero cost.
- (ii) No account has been taken of the fact that in some years the ambient temperature and incident solar energy may be lower. It has been suggested that long term solar energy storage systems in the U.K. should be oversized by 11% to account for this [11].
- (iii) No account has been made for the fact that the store will take 2 years before it acquires its full heat content.

- (iv) The cost of a backup heating system has not been included, though simple electrical heaters would do, and have low capital cost.
- (v) The cost of heat meters in each house has not been included: estimated cost is £80 per house [13].
- (vi) The Prometheus system would operate more efficiently if the collectors were tilted towards the south. This was not considered as suitable data was not available. The use of reflectors would also increase the energy collected for little extra cost, see Figure 2.30.

2.3.5 Energy Analysis

An energy producing technology should be a net producer and not a net consumer of energy over its lifetime. The analysis of energy inputs both in fuel and materials and the energy output in terms of useful energy for a new energy technology can provide some very interesting information. However, like economic evaluation, energy analysis does not alone reveal whether it is worth proceeding with a system, but rather that it cannot be ruled out. Energy analysis has the advantage over economics that the effects of inflation do not appear in the calculations.

$$\text{net energy requirement (n.e.r.)} = \frac{\text{energy input}}{\text{energy output}} = \frac{E_{in}}{E_{out}} \quad (2.10)$$

A value of less than 1 for the net energy requirement shows that a project has energy viability. This does not necessarily mean that projects with n.e.r. > 1 are not justified, because a very high grade source of energy may justify this criteria, e.g. electricity. However, it is not possible to establish a precise relationship between energy requirement and economic viability. But clearly the net energy requirement for low grade energy must be at least an order of magnitude or so less than 1 for economic viability, so an n.e.r. of 0.1 or 0.2 is a maximal criterion for realistic future economic promise [57]. For this reason an energy analysis of Prometheus has been carried out.

To perform an energy analysis of a system one requires a data base containing the energy cost of each item. It is important that the various inclusions and exclusions in a data base are known, as this can lead to apparent contradiction [58].

There are two types of energy inputs: gross, which is all energy processed and consumed during the lifetime, including the solar input, and net, energy which does not include the energy of the primary energy source being processed.

The net energy input is obtained from the inventory for construction, obtaining from a data base the energy input for

each single component which is determined by multiplying the relevant amount of the component, say, in tonnes or £, by the energy requirement of the material from which it is made, say, in gigajoules per tonne or GJ/£. These energy requirements indicate the total amount of energy resources measured in terms of primary energy required to produce a unit of energy output.

I have used four data bases in this analysis: [59], [60], [61], [62].

In the data base in reference [59] the total energy intensities for various products are quoted in kWh(t)/- (£1968). These have been updated to kWh(t)/ (£1978), which corresponds to the year of my inventory quoted prices.

To convert from the energy intensity (ϵ) in 1968 to 1978, I have multiplied by the cost of an average article in 1968 over that of the cost of the same article in 1978.

$$\epsilon (1978) = \epsilon (1968) \times \frac{\pounds(1968)}{\pounds(1978)} \quad (2.11)$$

This assumes that the change of commodity prices due to inflation has been faster than the technical progress in reducing the energy requirements to produce any article. The value for $\pounds(1968)/\pounds(1978)$ has been obtained from the general retail price index.

This data base also quotes the energy cost of each item as it

leaves the factory gates and does not include the energy required to heat and light stores and warehouses used to store and sell the product once it leaves the factory. For this reason, the final capital energy requirement has had 15% added to it as an on-site energy factor for the energy used in construction, storage and transportation [57].

Manpower has been given a zero energy requirement, as a saving in manpower does not lead to a saving for U.K. fuel consumption. Land is also given a zero energy cost.

Results

The total primary energy input into the capital construction, C , of Prometheus is 13.6×10^6 kWh(t) \pm 15%: see Table 2.4 for the breakdown of costs. The total primary energy input into running Prometheus, R , is 0.22×10^6 kWh(t) per annum.

$$E_{in} = C + RN \quad (2.12)$$

where N is the system lifetime.

$$E_{out} = (0.764 \times N) \text{ GWh(t)} \quad (2.13)$$

$$\therefore \text{ n.e.r.} = \frac{13.6 + 0.22 N}{0.764 N} \quad (2.14)$$

For a system average replacement time of 45 years n.e.r. = 0.68. The lifetime required for the system, that is when n.e.r. = 1, is 25 years.

These results are not very encouraging, suggesting that if a large scale production of interseasonal stores was started,

this would cause a fuel crisis, because large amounts of energy would be consumed in their construction and they would not produce more energy for a period of 25 years.

The items of major energy costs in constructing Prometheus are also those with the maximum uncertainty in their energy cost. The largest energy cost is that of the collector. The value used to calculate this is for a conventional collector as the only data available are for these, and this value is quoted to have an uncertainty of a factor of three. The energy cost for pebbles is very dependent on the distance they need to be transported, which depends on the distance to the local quarry. The sheet piling and concrete sections for the storage tank are obviously not the ideal energy solution to the problem of containment. So there is clearly potential for reducing the energy cost of Prometheus.

From this analysis it is clear that the energy input into constructing an interseasonal storage system should be taken into account or, for many years, the system may consume more energy than it produces. Ideally not only the energy input should be calculated but also the exergy since the construction of solar collectors consumes a higher quality energy, in the thermodynamic sense, than they produce. That is, the work potential of 1 J of energy at 20° C is about 1/10th of that of 1 J of oil used to construct the collector. At present not enough information is available about energy costings to perform such exergy calculations.

2.4 Conclusions

If solar energy is to play a significant role in meeting the energy demand of the U.K., the development of interseasonal storage is essential. The cost of an interseasonal storage system can be substantially reduced if a communal heat store is used instead of individual stores (provided the storage is in the form of heat). This is due to: small surface area to volume ratio reducing the heat loss; the reduction in store costs; and the fact the store size can be designed for the average energy user and not the most 'energy hungry' user. There is little improvement in storage efficiency for systems serving more than 50 houses. However there may be a case for building larger systems to decrease construction and maintenance costs. The U-value of the insulation should be of the order $0.06 \text{ Wm}^{-2} \text{ K}^{-1}$. Increasing the efficiency of the collectors heating an interseasonal store can dramatically increase the energy provided by the system as more useful energy can be collected in the autumn and winter.

Much work has been done abroad on the development of interseasonal storage systems, mostly utilizing water and the ground as the storage medium. For this reason an interseasonal storage system in the U.K. utilizing a pebble bed store was investigated. Although the system investigated showed the potential of being as economic as conventional fossil fuelled domestic heating systems, an energy analysis of the system showed that the system was not very productive

in energy terms, in that the system only supplied about twice the energy during its lifetime that was required to build and maintain it. The construction of many such devices simultaneously could on its own produce an energy crisis. It is therefore recommended that if similar systems are to be constructed a full energy analysis is carried out and taken into account during the design of the system, and steps be taken to eliminate high energy components.

Data extrapolated from the Swedish experience by Earth Resources Research (ERR) to the U.K. climate suggests that the constructing of a water interseasonal storage system would have a capital cost of £2400 (1980) per house compared to £5700 (1980) for a pebble bed system, Prometheus , see Table 2.6. The figure of £2400 (1980) per house compares well with that of £2215 (1980) for the Studsvik system in Sweden. The water system is larger, supplying 300 houses instead of the 100 by the pebble bed store, so the water system would be expected to be slightly cheaper. From this analysis it appears that the water store is more cost effective, the reason being that the cost of the pebble bed storage is higher and the storage volume is larger due to the smaller specific heat capacity. However, Table 2.6 also shows the results from modelling a water storage system at the Polytechnic of Central London (PCL). The capital cost of the system is £5480 (1980), twice that of ERR. This is for a smaller scale system, only heating 50 houses. Nevertheless this does not explain the large difference, which may be due

to the PCL system using low performance collectors compared to ERR and therefore requiring a larger collector area and storage volume. Also PCL have used current costs based on a system devised by Ove Arup. It is now felt these may be too low [69]. This highlights the importance of high performance collectors for this type of storage system.

There is however a problem in comparing the costs of these different systems as the comparisons should be made on an equal footing with regard to both the method of economic analysis and the technical specification. This is not the case with the results presented above which differ in the items included for costing and the price reductions available due to future development and mass production.

Table 2.7 shows the relative costs of different types of storage materials and highlights the advantages of the water systems, which are cheaper than pebble bed systems for interseasonal storage systems, provided that high performance collectors are used. However pebble beds can still perform a useful role in the application of solar energy. Small scale systems, for instance where the pebble bed is integrated in the house design, can incur little extra cost when carried out with the main house construction. Pebble beds also may be useful in cases where fossil fuels are expensive and an air heating system is to be used in conjunction with passive solar measures. Such systems may prove economic as in Peterborough [63] and Dublin [64]. They may also be useful

in applications where air heating is desirable as in crop drying.

It is important to realize that with interseasonal storage the store will only be charged and discharged once per year. This results in the fact that only extremely cheap solutions can fit economically. To achieve this aim this work has focussed on reducing the storage size by increasing the operating temperature. However an alternative approach is to utilize much larger stores but which have very low cost - for instance the ground. To reduce the heat loss in such systems may prove to be half as expensive as the higher temperature water stores. One such system already exists in France [65] where a sports hall is heated all year round by a ground heat store, itself heated by quick response air heating collectors.

2.5 Future work

The computer modelling of the thermal performance of Prometheus ('Sunstore') is untested and so requires some type of validation because the model contains many simplifications, such as no storage stratification. Ideally the model should be validated against direct measurements. However this would be very expensive and the funds were not available. It was therefore decided to construct a detailed model of a pebble bed store and of an air heating solar collector and to validate these models against small scale laboratory measurements with the aim of linking these models once validated to validate 'Sunstore'. I undertook the air collector development, the results of which are presented in the following chapters. M. Golshekan undertook the development of a pebble bed model, the results of which are to be presented in his thesis. The work of running these models together has so far not been undertaken.

Future developments are not likely to change the economic viability of interseasonal storage in the near future and in particular regarding the use of pebbles. Although developments in phase change materials are likely to reduce their cost, this is never likely to be low enough to make them of use to interseasonal storage. Various developments have recently taken place for storing heat in materials which need to be externally activated to release latent heat [66]. Although this would mean that systems could operate without

insulation, and hence not need communal storage, it is doubtful that they will ever be economical. The same applies to chemical and electrical storage, and so water and soil and rock will probably remain the materials of choice for interseasonal storage far into the future. Given that costs as low as £2000 per house (i.e. payback periods of ≈ 4 years) may be achievable in the U.K., it is essential that a full design study of interseasonal storage in the U.K. should be undertaken. This should investigate the merits of the most promising types of systems, utilizing solar ponds, inground storage and water tank storage. The use of these storage materials with novel types of solar collector, low temperature, concentrating tracking, evacuated tubes, etc., should be fully investigated, the systems optimized, and comparisons made under the same economical and technical specifications.

The possibility of combining the use of wind and solar energy utilizing the same interseasonal store needs investigation in the U.K., where high winds occur during the heating season and so reduce the amount of seasonally stored energy. Similar designs have been investigated in Sweden with costs which are very competitive to conventional fossil fuels [68].

The energy cost of constructing solar collectors has been identified as a crucial determinant of the usefulness of interseasonal storage. It is important that research should be carried out to design low energy cost solar collectors.

It has been shown that communal (or district) systems are necessary for interseasonal storage to be economic. The use of district heating systems may prove to be the largest barrier to utilizing solar energy for domestic heating. At present only 1% of the U.K. space and water heating is provided by district heating compared to ~ 40% in Denmark. This is mostly provided by combined heat and power stations (CHP). However the potential for CHP in the U.K. is enormous, and theoretically the heat energy from power stations can be seen as 'free'. Yet this energy, although free, is not used. So what chance does communal solar energy have when solar energy is capitally very expensive? Obviously in the U.K. there are obstacles to district heating. On the continent the expansion in district heating from CHP occurred in the post war period when Europe was in the grip of high prices for imported fossil fuels and a large amount of house rebuilding was going on, mostly in very large dense groups. Only in developing new towns are conditions likely to be as favourable in the U.K. again.

Even if district heating does become acceptable, solar will then have to compete against CHP. Nuclear CHP is ruled out as economies of scale favour large nuclear power stations and hitherto it has been the policy of the electricity industry to site large power stations away from large conurbations for safety. This means that the station would have to be away from the domestic heat load and so the distribution network

would be expensive. Coal fired CHP is therefore the most likely competitor to solar for district heating, as coal will remain relatively cheap in the U.K. The major problem here is the electricity supply industry which does not like being reliant upon the mine workers, whom they view as unreliable and a politically volatile source of primary energy. These suspicions extend to the railway workers and, unlike oil, coal must be delivered by rail, and power stations depend on continuous replenishment of stocks. The electricity supply industry feels itself to be in the front line, always held to ransom and in perpetual danger of having to introduce electricity cuts. These political, social and institutional advantages and disadvantages to the acceptance of solar district heating need to be investigated just as much as do the economic and technological ones.

Smaller scale 'micro-CHP' schemes are now being planned in the U.K. utilizing car engines, 'TOTEMS', to generate heat and electricity. Schemes of four TOTEMS heating 50 houses have been analysed and the economics appear favourable [70].

In the future, with the price of fossil fuels rising and the cost of photovoltaic cells dropping, such schemes may be replaced by solar micro-CHP using hybrid photovoltaic and air heating systems, see Section 4.1, Figure 4.3.

Although the economic assessment of an energy technology is essential, for this provides a means of assessing similar

technologies, there are difficulties when comparing dissimilar technologies such as solar and fossil fuels. Conventional economic theory assumes that the customer is supreme in dictating such issues as whether or not solar energy schemes are a good thing. This is the principle of 'sovereignty of the consumer'. Whatever the theory, however, it is apparent that consumers' interests are frequently, if not always, subservient to other interests. The normal means by which a consumer exercises his sovereignty is not available on the energy market. Once a decision to invest in a certain technology has been taken, say gas, a change to solar energy is not advantageous if the existing infrastructure already exists for gas. Also, if energy decisions were to be taken on a purely economic basis then the price for industrial gas should be cheaper than domestic gas since distribution costs are less. However, a political decision has been taken that gas is a valuable resource and too valuable to burn in large quantities.

CHAPTER 3 Insulation or Insolation?

3.1 Introduction

Chapter 2 investigated the potential for long term storage to provide heat for domestic consumption. The cost of meeting this demand by solar energy was then compared with conventional fossil fuels. However this comparison was complicated by the fuel inflation rate and discount rate. An alternative to this comparison is to compare to solar costs the benefits of reducing the energy demand via conservation measures. One could argue that by insulating a house the effective energy consumption of the house can be reduced to zero, so eliminating the need for heating, by fossil fuels or by solar energy.

This chapter investigates the level of insulation a house should have before it is economic to install an active solar heating system. Given an overall sum to spend on reducing the fossil fuel demand for heat for a conventional house, what proportion should be invested in improving the insulation, and what proportion in installing an active solar system? This is a very serious question for the future if interseasonal storage systems are to be built, and for the present with short term solar systems now being installed. The Department of Energy was recently criticized in a select committee report for not knowing if the cost benefit in investing in Nuclear Energy was better than conservation. A similar criticism can be made of the pro-solar lobby. In a

recent International Solar Energy Conference in Birmingham ('Solar Energy Benefits Evaluated', Sep'82) somebody posed the question 'when does it become profitable to stop investing money into conserving energy in house heating and start to invest in solar heating?'. No answer was forthcoming. This chapter addresses this very problem. The comparison of solar heating with insulation is less contentious because the investment decisions for insulation and solar heating are similar, in that they both involve a large initial capital expenditure and have low running costs, the relative benefits are not dependent on the rate of fuel inflation, and both measures have similar environmental impacts. For this reason it is unnecessary to worry about social discount rates, fuel inflation and environmental awareness.

The running costs of the solar heating system are not included, because for a carefully designed system they should be small when compared with the initial capital expenditure.

The difficulty in comparing the benefits of more insulation with adding a solar system, is that adding more insulation affects the benefits of installing an active solar system, because insulation not only reduces the peak demand for heating, but also the length of the heating season which, in turn, affects the useful energy a solar system can collect. So the useful energy provided by a solar system installed on a conventional house will differ from that for a well-

insulated house. This means that the benefits of a solar system must be evaluated for different levels of insulation.

This chapter not only examines the benefits of insulation and solar heating (with both long and short term storage) on new houses but also for existing houses. The latter will form the majority of our housing stock over the next 50 years.

Note that passive solar measures are classified as insulating measures in this chapter. All prices in this chapter are for mid 1982.

3.2 Analysis for New Buildings

The cost and energy savings which can be achieved by implementing solar and insulation measures are to be investigated when implemented on a basic type A0 house which is a new house built to 1975 Building Regulations.

3.2.1 Basic type A0 house

The basic A0 type house is a new 3-bedroom end-of-terrace house constructed to meet 1975 Building Regulations. A schematic diagram of the basic house design is shown in Figure 3.1. The basic thermal characteristics of the structure are shown in Table 3.1.

The house consists of unfilled cavity walls with thermolite blocks on the inside, and concrete floors plus 50 mm of loft insulation. Zero heat flow with the party wall into the next house has been assumed. The air changes once every hour in the house; this is independent of the level of insulation. Hot (60° C) water consumption for the house is 45 litres per person per day, which, assuming no seasonal variation in water demand, is equivalent to 0.77 GJ per month. 'Free' heat gain in the house due to body heat and electrical appliances is assumed to be 1.8 GJ per month for every month of the year. The house is situated at Kew, London (latitude 51° N) and experiences the average weather conditions during the years 1969 to 1977 - see Table 3.2. All the windows are

on the front and back of the house, which faces west. The net annual space and water heating demand for the basic house is 46.4 GJ, which is the amount of heat that has to be supplied by the space and water heating system.

3.2.2 Energy demand for different levels of insulation

The net space and water heating demand for a house in any month can be calculated using the following equation:

$$\begin{aligned} \text{Net heating demand} = & \text{gross space heating demand} - \text{free heat} \\ & \text{gain} - \text{useful solar gain} + \text{hot water} \\ & \text{demand} \end{aligned} \quad (3.1)$$

The gross space heating demand is calculated from the total house specific loss, multiplied by the number of 'degree days' in the month [1]. The 'degree days' in this paper are calculated assuming an average whole house temperature of 15.5° C, as this is more representative of average whole-house temperatures than the more commonly used value of 18° C [2]. The useful solar gain is calculated assuming that 41% of the incident radiation on single glazed windows facing south is useful, with 35% the figure for double glazing.

The analysis considers the application of discrete insulating measures to the basic building which reduce the space heating demand. The order of the insulating measures is first to install those which give the most return on fuel savings for a given amount of capital expenditure (the shortest payback

period). This analysis has been carried out by Everett [2] for the basic type A0 house. Table 3.3 shows the calculated net annual space and water heating demand for the various insulating options A1 to A11 progressively added to the basic type A0 house during construction.

Two 'passive' solar measures have been included in the options, and these are assumed not to increase the cost of the house. The first is to orientate the house so that all the window area is on the north and south sides of the house, and because the cost is zero, this is the first option. The second passive measure is to place all the windows on the south side - theoretically possible but in practice not desirable. Although the cost of this option is zero, it is not implemented at once, because the benefits obtained from reorientation in terms of reduced energy consumption are not seen to outweigh the disadvantage of having to use artificial light in the rooms on the north side of the building [2].

Figure 3.2 shows the space heating consumption of three of the types of houses, month by month. Note that not only does the peak demand of energy fall as the house becomes better insulated, but also the period of time for which heating is required, i.e. heating season also falls.

The continuous line in Figure 3.3 shows the extra construction cost for a basic type A0 house, against the useful energy saving per annum for the various measures A1 to

All in Table 3.3. In general, the steeper the line, the better the insulation measure. So the steeper measures should be implemented first (except, as noted, placing the windows on the south side) since as more conservation measures are introduced it becomes progressively more expensive to reduce the energy demand. Note that the costs refer to all the insulating measures being implemented together to the basic type A0 house, and that the current (1982) Building Regulations correspond roughly to a type A3 house.

It is important to remember that in this analysis it has been assumed that insulation does not effect the ventilation rate or the hot water requirement.

Reducing the ventilation rate can be very cost effective in energy terms. However this can cause problems of condensation and high levels of Radon which can be expensive to overcome.

The total energy savings calculated in Table 3.2 agree with those measured on similar houses in the Pennylands project [3].

3.2.3 Solar heating

The energy saved by installing various active solar heating systems to the type A0 house with varying levels of

insulation can be calculated. For long term storage systems the method outlined in Section 2.3.3 was used. For short term storage (the standard solar system available in the U.K.) the f-chart method [4] is used.

Standard solar system

The fraction f of the monthly load supplied by a standard liquid solar space and water heating system with 75 litres of water store per m^2 of collector can be calculated using the f-chart method:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (3.2)$$

where

$$X = \frac{\text{collector loss}}{\text{demand}} = \frac{A_c F_R U_L (T_{\text{ref}} - T_a) t_m}{L}$$

$$Y = \frac{\text{absorbed solar energy}}{\text{demand}} = \frac{A_c F_R (\tau \alpha) H_T N}{L}$$

Equation 3.2 has been derived empirically and applies only over a narrow range of parameters: see Duffie and Beckman [4] for the range. Equation 3.2 was applied to a type A1 and a type A5 house, fitted with a standard solar system consisting of a water-heating collector with a selective absorber and a 3 mm thick glass cover ($\tau \alpha = 0.8$), and having a collector/heat-exchanger factor of 0.8, a heat loss coefficient of $U_L = 4.5 \text{ Wm}^{-2} \text{ } ^\circ\text{C}^{-1}$, a water flow rate of 0.02 kg s^{-1} per m^2 of collector, orientated 30° to the horizontal facing south, and 75 litres of water store per m^2 of collector. Figures 3.4 and 3.5 show the month by month

energy supplied by 4, 12 and 24 m² of collector installed on the type A1 and type A5 house. The costs and annual energy savings for 4, 12 and 24 m² of collector mounted on a type A1 and a type A5 house are plotted in Figure 3.3, the points being connected by the short dashed lines.

The costs for the solar water heating system are based on the real costs of constructing a solar heating system in Milton Keynes [5] on a new house. The figures have been updated to 1982 using the Retail Price Index. It is assumed that the collectors are constructed on site and account has been taken of the reduction in building materials in the roof due to the collectors. It has been assumed that there are no economies of scale, that is, the same price per square meter of collector is paid for the 4 m² system as for 24 m².

The energy saving and cost of installing and operating an interseasonal storage system installed on a type A1 and a type A5 house were calculated in Chapter 2. The points for interseasonal storage lie to the right of Figure 3.3 and cannot be plotted. Instead the long-short dashed lines extend towards where these points lie.

The f-chart method is empirically based on solar heating systems installed in the U.S.A. and there is some doubt about its applicability to U.K. systems. There is only one fully reported and correctly operating solar heating system in the U.K. It is sited in Milton Keynes [5]. The results of the

heating demand and solar supply of the A1 type house fitted with 24 m² of collector, obtained from the f-chart method, are compared to those measured from the Milton Keynes solar house [5] Figure 3.6. The predicted figures using the f-chart, and the actual figures from the solar house, are reasonably close except during November, December and January, when the f-chart predicts too small a solar contribution, and so a more sophisticated model is required. This difference may be attributed to the low levels of radiation in the U.K. during the winter months and the transient nature of the radiation, see Chapter 6.

3.3 Analysis for existing houses (retrofit)

The analysis has to be modified for existing houses, because the measures that can be applied to them are limited. For example, it is not practical to reorientate a house, increase its glazing area or increase the size of its cavity. Long term storage is difficult, because the store is difficult to accommodate.

The costs for retrofitting are more expensive as contractors have to come especially on site, and savings in materials for roofing when installing collectors are not made. The costs assumed are for commercial installation and are greater than would be the case for 'do-it-yourself' installation by the house holder or installation while re-roofing.

3.3.1 Basic type B0 house

This house is the 'average' house presently in the U.K. building stock. The most common type of house is semi-detached [6] (33% of present housing stock), with external wall area 73.9 m², roof area 41.2 m² and window area 13.3 m². The majority of semi-detached houses have an uninsulated 50 mm cavity, are single glazed and have 50 mm of loft insulation. There are very few data on the orientation of existing houses, so we have assumed that half the window area is on the south side.

The basic thermal characteristics of the structure are shown in Table 3.4. The order of priority for introducing conservation measures to an existing type B0 house is the same as for new houses except that the measures which cannot be retrofitted have been missed out: see Table 3.5.

Figure 3.7 shows the cost of retrofitting various insulation measures to the basic house and the useful energy saved. Note the cost refers to the n measures being retrofitted to B0 in one go, so the additional cost of triple glazing is only the material cost. Also shown as a dashed line is the energy saved and the extra cost of installing a standard solar system with short term storage onto types B0 and B5 houses. The costs for the solar collector system are as quoted by commercial companies [7]. The same labour costs have been assumed for installing 24 m^2 of collector as 4 m^2 . The standard solar system in performance terms however is identical to that used on the type A1 and type A5 house discussed earlier.

3.4 Discussion and conclusions

Care should be taken in interpreting these results, because each building has its own characteristics, and there is no unique generalised solution to the problem. In addition, only the economic factors have been considered. For example, reduced noise, less condensation, and increased room area which is thermally comfortable, are also relevant. Figure 3.3 shows that installing active solar measures on a new uninsulated basic type A0 house is not a wise investment. The first £600 should always be invested in insulation to bring the standard of insulation up to a type A5 house. Conventional solar systems should only then be considered. But it appears doubtful that installing more than 4-12 m² is a wise investment, because once the instantaneous hot water demand has been supplied by the collector area the decrease in heating demand is small with short term storage. The gradient of the line for long term interseasonal solar heating (and so the Joules per £ invested) does not change dramatically from the type A1 to the type A5 house, and is approximately 4.2 MJ/£ (for the pebble bed storage system described in Chapter 2). This is because interseasonal storage is not dramatically affected by a change in the length of the heating season. It would appear that the kind of interseasonal storage envisaged here (i.e. pebble bed, etc.) only becomes a cost effective option once the house has been insulated to a standard similar to type A9. But if money is still available once this level of insulation has

been achieved, communal interseasonal storage would appear a wise option.

From Figure 3.7 we can conclude that it is uneconomic to install a conventional water fed solar hot water system on the 'average' U.K. house if the installation is to be carried out by a commercial organisation. The money would be better invested in further insulation. Only if a house has been insulated to the standard of a type B5 house does the standard solar system become more economic than further insulation. This does not mean that it is always uneconomic to install solar heating when compared with conservation on an 'average' U.K. house. There may be circumstances where insulating the house is very difficult, such as solid walls or enclosed lofts. Also, if the unit cost of water heating is not the same as that of space heating (for instance, if the house is heated by gas or coal, and the hot water by electricity), then the solar measure could save more money than the insulation, which influences only the space heating, although the energy saving would be less. These circumstances are likely to be in the minority, bearing in mind that 33% of lofts have no insulation, 75% of semi-detached houses have 75 mm or less of loft insulation, 91% of semi-detached houses with cavities have them uninsulated, 82% of semi-detached houses have single glazing, and 25% of houses with domestic hot water tanks have no insulation on them.

It is thus suggested that before houses in the U.K. are

fitted with conventional solar systems, they should be insulated to a much higher standard than either the average for existing houses, or the standard for new houses built according to 1982 Building Regulations (similar to type A3). Some commercial solar heating firms do not advocate insulating houses, because the insulation reduces the heating requirement; although this means that the fraction of energy provided by the solar system is larger, the total substituted amount of fuel is less, and therefore it is argued that a solar heating system is less economic on a well-insulated house than on an uninsulated house! This paper shows that this is not the case, and that in most cases a house should be heavily insulated before a conventional solar system is installed. However, if improvements in solar systems are achieved through novel designs involving low-cost systems or high-efficiency collectors, the levels of insulation required before solar systems become more cost effective than further insulation may lie below the insulation level demanded by the Building Regulations. Were this to become the case, there would be a strong argument for including solar heating systems in the Building Regulations.

Chapter 4 Air heating solar collectors

4.1 Preamble

The first active air heating solar collector was patented in 1897 [1]. Since then some 20 patents have been taken out for different air heating designs. All solar air heaters can be classified under two categories. The first type has a non porous absorber in which the air stream does not flow through the absorber plate but may flow above and/or behind the absorber plate. Collectors with air flow just below the absorber plate are known as 'rear-duct' collectors, Figure 4.1(a), whereas if the flow is above the absorber they are known as 'top duct', Figure 4.1(b). It is also possible to have air flow above and below the absorber. The second type has a porous absorber that includes slit and expanded metal, transpired honeycomb, and overlapped glass plate absorbers, Figure 4.2. For an extensive review of air heaters I refer the reader to 'Air heating solar collectors' by I. Wiles [2] and 'The improvement of solar air collectors' by B.E. Cole-Appel et al [3].

Air heating solar collector systems have several advantages over liquid systems;

- (i) They do not freeze or boil, a condition frequently met in the United Kingdom for liquid collectors.
- (ii) They do not corrode as much as liquid collectors.
- (iii) They can be used in conjunction with pebble bed

stores which offer the advantage of stratification and so higher system efficiencies than water stores.

- (iv) They require less maintenance [4].
- (v) Leaks do not cause damage.
- (vi) Direct space heating is possible.
- (vii) Shorter reaction times when the collector is under stagnation.
- (viii) Lower collector costs, because the fluid mass is less and the conductivity of the absorber plate is not so important.
- (ix) At low insolation levels air collectors have substantially higher collector efficiencies [5].

There are also several applications for solar thermal energy which favour the use of air collectors because the use of a liquid heat transfer fluid is not desirable.

- (i) Crop and industrial drying where air is the drying fluid and so the air handling and distribution system already exists.
- (ii) Hybrid with passive solar measures (now popular in the U.K.) [6] [7] [8].
- (iii) Hybrid with photovoltaic conversion. Photovoltaic conversion only converts $\approx 10\%$ of the available solar energy to electricity. The remainder heats the photovoltaic cell which in turn decreases its efficiency. By cooling the cell with air the thermal energy can be collected and the electrical efficiency

kept high [10] [11]. This concept may prove to be even more important with the next generation of photovoltaic cells [12], Figure 4.3. The photovoltaic cells are enclosed in a vacuum which reduces the heat loss from the cell and so overheating may become a bigger problem, requiring some type of forced cooling. Water can be used [13] but is less attractive.

Disadvantages with air systems are;

- (i) They require more space for the fluid carrying ducts, because air has a lower volumetric heat capacity than water, and also more space for the store because pebble stores have a lower volumetric heat capacity than water.
- (ii) Leaks are difficult to detect and yet can substantially reduce system efficiency ([5] - and Chapter 5).
- (iii) They require careful design of fan and duct work to avoid excessive parasitic power (power required to extract energy from the collector, in this case power for the fan). Too small a flow rate can dramatically reduce the collector efficiency. Too large a flow rate can cause excessive pressure drops in the duct work and across the collector, resulting in too large parasitic power. Nevertheless by careful design it has been reported that air systems appear to use less

parasitic power than water systems [14].

The degree to which the advantages outweigh the disadvantages depends on the particular site and application. However, when the solar heating systems on two identical adjacent houses, one a water system and the other an air system, were compared over an identical season, it was concluded that they both had a similar performance but that 'An air system should have more appeal for residential space heating where low value space can be provided and where maintenance must be low' [15].

The majority of work on solar air heaters has been carried out in the United States. There are only a few operational solar air heating systems in the United Kingdom (see Table 4.1) where the majority of interest has been in water heating collectors. Out of 21 experimental active solar heated houses in the U.K. reported in 'Solar Energy Today' [6], only one uses air as the heat transfer medium. There is only one fully monitored and reported solar air heated home, built by Wimpey [4], and one test facility for air heating solar systems, at BSRIA [16]. The major use of solar collectors in the United Kingdom has been the supply of domestic hot water with water as the heat transfer fluid. However there appears to be no reason why high performance air heating collectors with air to water heat exchangers cannot achieve the same performance as water systems [2]. In another study of solar assisted space heated buildings completed in Britain by mid

1979 [17] only two out of 27 houses reported had air heating systems. The report concludes that the preference for liquid collectors in Britain could be due to one particular solar architect designing the majority of early solar systems in Britain. This seeding process led to the familiarity of liquid plumbing design details and a reaction against the use of air collectors. This reaction must also be partly due to the very low efficiency of 14% achieved by the Wimpey house [4], the major United Kingdom demonstration project of air heating. However, the Wimpey demonstration highlights the importance of correct design for air systems, and is not a fair reflection of their potential.

A lack of testing facilities, standards and an indigenous technology for air heating collectors in the U.K. has led to few experimental systems and to those which have been produced being incorrectly optimized. This in turn has led to a lack of interest in the U.K. in air systems and to little research, breeding a vicious circle. The rest of this chapter, and the next chapter, attempt to add some experience and knowledge to help break this vicious circle. This chapter is mainly theoretical. Then, in Chapter 5 two very different air heating collectors, both designed according to current good practice, are examined by testing them and by comparing their performance against sophisticated and simple models. Both are flat plate. The first collector (labelled DC Hall) is a sophisticated state of the art rear duct collector, using the best design characteristics, to

give a high performance collector in which the potential for top loss reduction can easily be investigated. The collector is also thermally massive. The second type of collector (labelled structured polycarbonate) is very cheap, easily manufactured from plastic, and has a very short time constant. It is a top duct, though a rear duct version could readily be made. The effects of heat capacity and top loss are investigated, and also the methods for testing air collectors.

4.2 Theory of flat plate air heating solar collectors

4.2.1 Steady state case

The theory of flat plate collectors in the steady state or equilibrium state has been discussed in great detail. For a detailed overview of the subject the reader is referred to Duffie and Beckman [18]. However a brief restatement is presented here, to highlight the assumptions made in comparing the theoretical and experimental results, to provide a background for the experimental work, and to update the results presented in Duffie and Beckman.

The energy balance of a flat plate solar collector (in the steady state) is given by Duffie and Beckman as

$$Q_U = A[I(\tau\alpha) - U_L(T_p - T_a)] \quad (4.1)$$

where $(\tau\alpha)$ is the effective transmittance-absorptance product for direct radiation at normal incidence to the cover. For diffuse radiation and angles other than normal this must be corrected (see section 5.3). The transmittance τ of the cover material can be obtained from the Fresnel equations [18] or by measurement. The effective transmittance-absorptance product $(\tau\alpha)$ is slightly larger than the product of τ times α since the radiation not absorbed by the absorber is not all lost but some is reflected back by the cover system to the absorber plate. Duffie and Beckman suggest that a reasonable approximation for most practical solar collectors is

$$(\tau\alpha) \approx 1.01 \cdot \tau \cdot \alpha \quad (4.2)$$

4.2.1.1 Rear duct

U_L the collector overall heat transfer (loss) coefficient is made up of losses from the collector back, U_b , top, U_t , and edge, U_e (see Figure 4.4). Thus

$$U_L = U_t + U_b + U_e \quad (4.3)$$

The back loss for a well designed collector should be small and can be approximated by

$$U_b = k/x \quad (4.4)$$

where k is the thermal conductivity of the insulation and x its thickness. For either very thick or very thin insulation a more complicated formula may need to be used.

The edge loss for a well designed collector where U_e is small compared to the other losses can be approximated by

$$U_e = \frac{(UA)_{\text{edge}}}{A} \quad (4.5)$$

where A is the collector area and $(UA)_{\text{edge}}$ is the 'edge loss coefficient area product' obtained by assuming there is only one-dimensional heat loss perpendicular to the edge.

$$(UA)_{\text{edge}} = \text{area of insulation around perimeter} \\ \times \frac{\text{edge insulation thermal conductivity}}{\text{thickness of edge insulation}}$$

The top loss is dependent on the collector configuration: we shall be considering two types, the rear duct, Figure 4.5, and the top duct, Figure 4.6.

For rear duct collectors

$$U_t = \left[\frac{1}{h_{p-c} + h_{rp-c}} + \frac{1}{h_w + h_{rc-a}} \right]^{-1} \quad (4.6)$$

where h_{p-c} is the convection coefficient between the absorber plate and the cover and is dependent on the tilt angle of the collector, the plate to cover spacing and the gas between the plate and cover, and is discussed in great detail in Chapter 7.

h_{rp-c} is the radiation coefficient from the plate to cover and is dependent on their surface properties ϵ_p and ϵ_c .

$$h_{rp-c} = \frac{\sigma (T_p^2 + T_c^2) (T_p + T_c)}{1/\epsilon_p + 1/\epsilon_c - 1} \quad (4.7)$$

assuming diffuse surfaces, large compared to their separation.

h_{rc-a} is the radiation coefficient from the cover to the sky. The sky can be considered as a blackbody at some equivalent sky temperature so that the radiation transfer coefficient between the cover and the sky is given by

$$h_{rc-a} = \epsilon_c \sigma (T_c^2 + T_{sky}^2) (T_c + T_{sky}) \quad (4.8)$$

assuming diffuse surfaces where the cover area is very small compared to the sky area. The sky temperature is nearly always less than the ambient temperature and can vary depending on the cloud cover and humidity. Since

T_{sky} is difficult to predict and the other heat loss coefficients are with respect to ambient, when calculating h_{rc-a} the ambient temperature can be used instead of the sky temperature, but twice the value of h_{rc-a} is then to be used for the rest of the analysis to compensate for the lower temperature of the sky (see Section 4.2.2).

h_w is the wind heat transfer coefficient. Various correlations have been proposed for h_w [18], and there is confusion over which correlation to use.

The most commonly used equation because of its simplicity, is that reported by McAdams [19] from experimental data by Nussett and Jurges [20] (performed in 1922) and quoted in Duffie and Beckman [18] as

$$h_w = 5.7 + 3.8 V \quad (4.9)$$

It is probable that in this equation the effects of free convection (at low wind speed) and radiation are included. However, radiation loss varies with the sky temperature and is independent of the wind speed. Therefore Watmuff et al [21] reported that the equation should be

$$h_w = 2.8 + 3.0 V \quad (4.10)$$

However, this equation still takes no account of the variation of free convection caused by changes in the ambient and cover temperature. It also ignores collector size and orientation. Its application is

therefore very limited.

Sparrow et al [22] did wind tunnel tests on rectangular plates at various orientations and found the following correlation for plates of length, L , and width, W , over the Reynolds number range of 2×10^4 to 9×10^4 m in moving air with zero angle of attack.

$$h_w = \frac{k \times 0.86 \times Re^{1/2} \times Pr^{1/3}}{D_h} \quad (4.11)$$

where

$$Re = (D_h) \frac{\rho V}{\mu}, \quad Pr = \frac{C_p \mu}{k.L.W.}, \quad \text{and } D_h = \frac{2.L.W}{(L+W)}$$

and V is the free field wind speed and not the wind speed across the collector, which will be less.

For a 1×1 collector

$$h_w = 5.0 \sqrt{V} \quad (4.12)$$

where h_w is virtually independent of T_c and T_a . However, equation 4.12 does not hold in still air since as V tends to zero, h_w also tends to zero, thereby failing to account for free convection, so some other empirical expression is needed at low V . Lloyd and Moran [23] give the following relationship in still air for horizontal flat plates with aspect ratios up to 7:1.

$$h_w = \frac{0.15 \times Ra^{1/3} \times k}{(D_h)} \quad \text{for } 10^7 < Ra < 3 \times 10^{10} \quad (4.13)$$

where

$$Ra = (D_h)^3 \Delta T \frac{9 g C_p \rho^2}{\mu.k.L.W.} \quad (4.14)$$

and $\Delta T = T_c - T_a$.

For square collectors this changes little with the tilt angle of the collector.

Note also that h_w in still air is significantly dependent on T_c and T_a . For comparison the correlations of McAdams, Watmuff and Sparrow ($T_c = 13^\circ\text{C}$, $L = W = 1 \text{ m}$) are plotted in Figure 4.7. Also plotted is the point for still air as predicted by Lloyd. Note that the Sparrow correlation is only defined for $Re > 2 \times 10^4$ and so $V > 0.3 \text{ m s}^{-1}$ and at this velocity has a lower value of h_w than the Lloyd relation at 0 m s^{-1} . It therefore appears that Sparrow's relationship only holds down to $\approx 1 \text{ m s}^{-1}$. Also plotted on Figure 4.7 is a correlation of Green [24] which is a more complicated combination of a free convective heat transfer coefficient h_o developed by Fussey and Warneford [25] and a convective heat transfer coefficient h_f of Sparrow [26].

$$h_w = (h_o^{3.5} + h_f^{3.5})^{1/3.5}$$

The Sparrow and Lloyd relationship plotted in Figure 4.7 agrees well with Green's. Green's correlation has shown good agreement with indoor measurements [24] provided a correction factor of 3 is used to convert the free wind speeds (or meteorological wind speeds) to air velocities parallel to a

horizontal collector surface (windspeed across collector).

This correction factor is consistent with measurements performed by Oliphant [27] of meteorological wind speeds and wind speeds across the collector.

So far none of the relationships mentioned are based on experiments performed in conditions truly representative of those encountered by solar collectors in typical installations, that is, where the collector is mounted on a building and subject to natural wind which is very turbulent and which has a mean velocity varying with height. Kind et al [28] have measured h_w for a scale-model collector array (equivalent in size to 6 flat plate collectors 1.2 m x 2.4 m high) mounted at a height of 4.5 m on a model representative of a two-storey, solar heated, single family residence. The model was tested in a wind tunnel in which the characteristics of the natural wind were simulated. The heat transfer coefficient was found to be insensitive to the characteristics of the wind and to architectural details of the building but to be sensitive to the wind direction, being highest when the plane of the collector array is aligned with the wind direction (for ϕ , azimuthal angle = 90° , see Figure 4.7), and lowest when the collector array is on the leeward side of the building ($135^\circ < \phi < 180^\circ$), for a collector tilt angle of 60° to the horizontal.

By comparing the above correlations it appears that the simplest relationship to use, without encountering undue

error, is that of Lloyd and Moran for still air conditions, and Sparrow et al for moving air ($V > 1 \text{ m s}^{-1}$) and to interpolate between these two for $0 < V < 1 \text{ m s}^{-1}$. The correlations of McAdams and Watmuff do not hold for meteorological wind speeds since they give wind heat loss coefficients twice the true value. For collectors mounted on houses with a known prevailing wind direction the results of Kind et al should be used.

4.2.1.2 Top Duct

For the top duct collector the top loss is as if there were no cover on a rear duct. Thus with the plate relabelled as the cover, see Figure 4.6

$$U_t = h_{rc-a} + h_w \quad (4.15)$$

where h_{rc-a} and h_w are the same as before. However the overall heat loss from the collector is more complicated because the heat transfer fluid flows above the absorbing surface and so affects the heat loss, and equation 4.3 no longer holds. Instead,

$$U_L = \frac{(U_b + U_t) (h_1 h_2 + h_1 h_r + h_2 h_r) + U_b U_t (h_1 + h_2)}{h_1 h_r + h_2 U_t + h_2 h_r + h_1 h_2} \quad (4.16)$$

where U_b and U_t are as before and h_1 , h_2 and h_r are heat transfer coefficients within the fluid duct: h_1 is the convective heat transfer from the cover to the fluid, h_2 the convective heat transfer from the absorber to the fluid and h_r the radiation transfer between cover and absorber [18].

4.2.1.3 Alternatives to equation 4.1

Although correct, equation 4.1 is not a very useful equation because T_p is difficult to measure and not very useful for defining the useful energy collected that is associated with the temperature rise of the air as it passes through the collector. So, to define the collector operation in terms of the more useful fluid inlet temperature, T_i , we must introduce the collector heat removal factor, F_R , such that

$$F_R = \frac{\text{Actual useful energy collected } (Q_u)}{\text{Useful energy which would be collected if the entire absorber plate were at the fluid inlet temperature}} \quad (4.17)$$

$$\text{So } Q_u = F_R A [I(\tau\alpha) - U_L (T_i - T_a)] \quad (4.18)$$

sometimes known as the Hottel-Whillier equation.

F_R can then be shown to be [18]

$$F_R = \frac{mC_p}{A U_L} \left[1 - e^{-\frac{A U_L F'}{mC_p}} \right] \quad (4.19)$$

where F' is the collector efficiency factor, and represents the ratio of the useful energy gain to the useful energy gain that would result if each point on the collector absorbing surface had been at the local fluid temperature. The collector efficiency factor is essentially a constant for any collector design and fluid flow rate.

Expressions for the collector efficiency factor for different types of air heating collectors have been derived by Duffie

and Beckman [18] and Parker [29].

The efficiency factor for the rear duct air heater is

$$F' = \frac{1}{1 + \frac{U_L}{h_1 + (\frac{1}{h_2 + h_r})}} \quad (4.20)$$

and for the top duct air heater

$$F' = \frac{h_r h_1 + h_2 U_t + h_2 h_r + h_1 h_2}{(U_t + h_r + h_1) (U_b + h_2 + h_r) - h_r^2} \quad (4.21)$$

These equations show that the collector efficiency factors are dependent on the convective h_1 , h_2 , and radiative, h_r , heat transfer coefficients within the collector duct.

The convective heat transfer coefficients, h_1 , h_2 , are very dependent on the duct dimensions, the type of flow (turbulent or laminar), the entrance configuration, and the fluid flow rate. The accurate measurement of the convective heat transfer coefficient for a rear duct air heating collector has been carried out by Wiles [2]. However for the purpose of this analysis it was considered adequate to use the relationship used by Cole-Appel [30] et al based on experiments by Tan and Charter [31], which applies to a prismatic duct, with no fins or other obstructions.

$$h_1 = h_2 = \frac{k \cdot Nu}{D_h} \quad (4.22)$$

where

$$Nu = Nu_{\infty} (1 + S D_h)/L \quad (4.23)$$

for $9500 < Re < 22000$. However the lower limit can be lowered to ≈ 2000 if the passage is rough and/or entry is sharp-edged. Now

$$Nu_{\infty} = 0.0158 Re^{0.8} \quad (4.24)$$

$$\text{where } Re = \frac{m D_h}{W H \mu} \quad \text{for air in a rectangular duct} \quad (4.25)$$

where L = duct length

W = duct width

H = duct height

D_h = hydraulic diameter = $2 W.H/(W + H)$ ($\approx 2 H$ for small H/W)

$$\begin{aligned} \text{and } s &= 1.43 \log (L/D_h) - 7.9 && \text{for } L/D_h < 60 \\ \text{or } s &= 17.5 && \text{for } L/D_h > 60 \end{aligned} \quad (4.26)$$

Note that if the rear duct is divided into several compartments then W is the compartment width and m the mass flow rate in the compartment.

The radiative heat transfer h_r for two infinite parallel plates temperatures, T_1 , T_2 , and emissivity ϵ_1 , ϵ_2 is (compare eqn. 4.7)

$$h_r = \frac{\sigma (T_1^2 + T_2^2) (T_1 + T_2)}{1/\epsilon_1 + 1/\epsilon_2 - 1} \quad (4.27)$$

If T_1 and T_2 are close together then

$$(T_1^2 + T_2^2) (T_1 + T_2) \approx 4 \bar{T}^3 \quad (4.28)$$

where \bar{T} is the average duct temperature $(T_1 + T_2)/2$

Duffie and Beckmann [18] assumes that \bar{T} is the same as T_m , the mean fluid temperature. According to Wiles [2] this gives lower values of h_r than measured due to lower fluid temperatures than either plate temperatures (see Section 5.5). However, Wiles' results are not dramatic, because although there is some improvement in accuracy using duct temperatures instead of fluid temperatures when comparing theory with experiment, the increase in accuracy is only a few percent. So the extra accuracy does not appear to warrant the extra complexity in calculations and so the following relationship is used

$$h_r = \frac{4 \sigma T_m^3}{1/\epsilon_1 + 1/\epsilon_2 - 1} \quad (4.29)$$

where T_m is defined as $(T_i + T_e)/2$.

Equations 4.2 to 4.29 allow the calculation of the steady state efficiency for a top duct and rear duct air heating collector. Figures 4.8 and 4.9 show the flow diagram of a computer model written in Basic (see also Appendix B for listing). These programs allow the comparison of measured and theoretical efficiency and elucidate the effect of changing environmental parameters, collector geometries, and mass flow rates.

4.2.2 Transient case

The steady state model pays no attention to the mass of the constituent parts of the collector, which means that a zero

time is assumed for the energy to be transferred from one part of the collector to another. The effects of mass only become important under transient conditions and most collector tests are carried out under quasi-steady-state conditions, for which time-dependent effects are relatively unimportant in most cases. However, the operating conditions of collectors in the United Kingdom (and elsewhere) are predominantly transient (see Chapter 5).

The view that the transient response is not a particularly important property is supported by the early work of Klein et al [32], who concluded from work using just hourly data that collector energy outputs predicted by transient response models do not differ by more than a few percent from those predicted by time-independent models, and that the difference is essentially negligible for performance predictions based on hourly meteorological data. In view of this it was felt that complex multinodal dynamic models will do. Consequently little work has been done on the transient response of collectors.

Recently however, there has been a resurgence of interest in transient modelling because it has been felt that Klein's conclusions tell more about the usefulness of hourly data than about collector dynamics [33] and that they are based on the assumptions that solar collectors are characterized by response times of no more than a few minutes, whereas liquid collectors (in particular evacuated tube collectors) and air

collectors under flow conditions can have response times in excess of 30 minutes [34]. Also the total energy is not always of paramount importance. It may happen that for a particular application the grade or temperature of the collected energy is of more importance. For example, solar air heaters may be required to warm up incoming air to heat occupants in the building. The air outlet temperatures from long and short time response collectors to intermittent solar radiation are shown in Figure 4.10. Both collect the same amount of energy. However, if there is a critical temperature which the air into the house must have before the occupants feel warmer, then the long time response collector will not provide any useful energy in this sense. The transient response of collectors also has an important effect on the solar system control, which can have important effects on the system efficiency. This is particularly the case with air heating systems where variable mass flow rates may be used to optimize a system [35].

Several transient models have been developed. Their various features are reviewed by Mather, Jr. [34]. All these are however specifically for modelling the performance of liquid heaters. Air heaters differ in their transient response in two important ways. Under flow conditions, air collectors generally have time constants 3 to 15 min [30] [36] compared to 1 to 5 min [18] [37] for liquid collectors (with the exception of evacuated tube collectors). Under stagnation (no fluid flow) the time constants for air collectors either

increase by a factor of about five, or may not increase at all, as can be the case for top duct collectors, where under flow conditions the cover and absorber must warm up whereas under stagnation only the absorber warms up. Under stagnation the time constants for liquid collectors are nearly always larger than for air collectors.

Two transient models of air heating collectors have been found in the literature. The model of Garg et al [38] is for a top duct collector and that of Yussuff [39] is for a rear duct collector with a V shaped absorber.

To examine the effect of transient testing, zero radiation testing and the effect of different capacitances on rear duct collectors operating under transient conditions, typical to those experienced in the U.K., a dynamic multi-node model (RRDCT) of a rear duct air heating collector developed by B.W. Jones [40] (Appendix C) was used. The nodal configuration is shown in Figure 4.11. The model is more sophisticated than normal for transient models; equation coefficients can vary with temperature if they explicitly include temperature; the heat transfer coefficients coupling the plate and duct base to the air vary along the duct in the x-direction (along the absorber plate); thermal conduction along the plate and along the duct-base in the x-direction is included. The same heat transfer equations are used as explained in section 4.2.1 except they are applied to the separate nodes and not to the collector as a whole. Also,

the sky has a separate node which is at a temperature lower than ambient. The model was tested by comparing its predictions with the actual behaviour in the indoor testing (see section 5.4) of the D.C. Hall collector with a Nextel absorber (see section 5.1.1). Figure 4.12 shows an example of this agreement. Moreover, the slight discrepancy in response time can be put down to a greater spatial distribution of thermal capacitance in the laboratory collector, largely associated with a duct-base support frame which extended into the back insulation. Such a support frame could have been eliminated had rigid back insulation been used. With such caveats in mind, in all cases the agreement between prediction and actuality was good. To test the validity of using a single node model, the efficiency curve generated by RRDCT under steady state conditions is compared with the efficiency curve generated by the steady state model. Figure 4.13 shows that the steady state model gave a 2% higher efficiency at higher inlet temperatures. This was found on closer examination to be due to a higher sky temperature in the steady state model. This could be roughly compensated by doubling h_{rc-a} . The simplification of assuming an average plate temperature and heat transfer coefficient for a rear duct collector is justified, if this correction is made.